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High Frequency (HF) Upgrade Study for the Canadian Regional Operations Control Center (ROCC) AWACS Digital Information Link (RADIL) Project

By

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The Regional Operations Control Center AWACS Digital Information Link/Rapidly Deployable Integrated Command and Control System (RADIL/RADIC) Systems Program Office, Canadian RADIL Program, has acquired high-frequency (HF) radio equipment for two Canadian ground stations under the RADIL Project. This equipment will allow those stations to carry out Tactical Digital Information Link (TADIL) A data transmissions assisted by MIL-STD-188-141A automatic link establishment (ALE). The MITRE Corporation has been tasked to study whether U.S. TADIL stations should be equipped with similar HF-ALE modems. This report analyzes the improvements in performance over northern links that can be expected from the addition of ALE to the TADIL A system. Since there is only a small amount of data on ALE-assisted digital communications in northern regions, the analysis combines a probabilistic approach to comparison of ALE and conventional linking techniques with actual HF propagation data from links in Canada, Iceland, and Norway. The report also assesses the risks to effective communications of using an ALE-TADIL A system in the north and recommends several improvements in hardware and software that can lower those risks.

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EXECUTIVE SUMMARY

The Regional Operations Control Center Airborne Warning and Control System (AWACS) Digital Information Link/Rapidly Deployable Integrated Command and Control System (RADIL/RADIC) Systems Program Office (ESC/TN), Canadian (RADIL) Program, has acquired 1-kilowatt, high-frequency (HF) independent sideband (ISB) radios and FED-STD-1045/MIL-STD-188-141A Automatic Link Establishment (ALE) modems to equip two ground stations in Debert, Nova Scotia, and Edmonton, Alberta. This equipment provides the ability to carry out ALE-assisted Tactical Digital Information Link (TADIL) A communications with AWACS surveillance aircraft. These two stations are part of the Canadian RADIL system. The RADIL/RADIC Systems Program Office is considering equipping six additional TADIL A ground stations in the northern half of the western hemisphere with the ALE capability.

To determine if the ALE enhancement should be made operational at the six sites in question, MITRE has been tasked to determine the "mission availability" that can be expected from using ALE for long-haul HF communications with AWACS aircraft flying in northern regions. (Northern regions are roughly those lying above 50 degrees north latitude.) Mission availability is defined as the percentage of operating time a frequency can be found that will allow TADIL A data transfer from all TADIL A net participants to the current net control station (NCS). This report will focus primarily on communications exclusively in northern operating regions, although its results and recommendations will apply (with possible modifications to account for longer links) to RADIL communications between northern stations and those at midlatitude.

Mission availability of TADIL links operating with ALE is to be compared with that achieved using the present, operator-intensive concept of operations for setting up TADIL A network communications. Informal discussions with AWACS operators of the 552nd Air Control Wing at Tinker AFB suggest that the current procedure for setting up TADIL A links leads to successful linking about 70 percent of the time in all operating regions. The Systems Program Office would like to learn if ALE will raise the probability of linking high enough to ensure that the RADIL system communications are successfully completed 90 percent of the time in northern regions. (According to an informal survey of flight crews, the current approach is said to lead to successful *communications* between 50 and 70 percent of the time.)

This 90-percent communications availability requires not only that the linking probability be high but also that links last long enough to allow completion of the TADIL A mission. The concept of a link's lasting long enough for the mission concerns not only the ability of ALE to quickly find "useful" channels, but also the TADIL modem's ability to use those channels to carry out the TADIL A mission. Therefore, answering the RADIL availability question involves study of a fairly complicated interaction between the performance of an ALE modem and the performance of the TADIL equipment on usable frequencies found by ALE.

If the availability can be raised significantly (by between 10 or 20 percent), the ALE system would be used initially as a means for channel assessment alone. Later, ALE might be used in conjunction with TADIL A modems as part of an upgraded, fully automatic linking and data transmission system.

The ground station hubs for which equipment has already been acquired are located in east- and west-central Canada. The contemplated additional stations are in the contiguous United States, Hawaii, and Alaska. The AWACS aircraft that will be communicating with the ground stations will often be flying in the northern or extreme northern hemisphere.

THE HF COMMUNICATIONS ENVIRONMENT

Communications in the northern regions, where much of the HF communications between the RADIL and AWACS takes place, are often affected by poor HF propagation caused by auroral and polar ionospheric phenomena. These phenomena arise from the relatively small amount of direct solar illumination experienced in the north, from the relatively large amount of particle precipitation that arises in connection with auroras, and from magnetic-field-aligned irregularities resulting from the magnetic field lines in polar regions that are nearly perpendicular to the earth.

Even when frequencies support propagation in the northern regions, the resulting communications are often poorer than they would be at midlatitudes because of fading and intermittent propagation failures caused by field-aligned irregularities and auroral ionization effects. These comparatively poor communications thus have two main properties: useful frequencies generally last for shorter periods (especially at night), and useful frequencies are affected by fading and longer term intermittencies more often than at midlatitudes.

The current concept of operations for HF data communications with AWACS aircraft starts with predicting a subset of the assigned frequencies that will work for a particular TADIL A net on a given day. To determine the set, a local frequency manager uses a combination of standard propagation programs, such as MINIMUF or IONCAP, and short-term measurements of the daily sunspot number obtained from an on-line service, such as that provided by the Air Force Global Weather Center at Offutt AFB in Nebraska. These data are sometimes supplemented with on-line predictions of HF propagation anomalies caused, for example, by auroral and other polar events.

The standard propagation programs give predictions of the lowest usable frequency (LUF) and the maximum usable frequency (MUF) that will be achieved on a link at a given sunspot number on a given day in a given month. The local frequency manager compares his list of assigned frequencies with the daily MUF and LUF and produces a subset of the assigned frequency set that lies between the LUF and MUF. This subset is usually chosen to be as close to the MUF as possible, to take advantage of the generally better propagation at frequencies below but near the MUF.

The subset typically comprises three or four frequencies, listed in the order of best-to-worst frequency in terms of expected signal-to-noise ratio (SNR). The TADIL A net control station (NCS) tries one of the frequencies in the subset. If its poll of the net shows that TADIL A network communications work on the chosen frequency, then that frequency is used for the TADIL A net. If one of the net members (including the NCS) later finds that the net frequency has failed, or is beginning to fail, it uses an HF voice orderwire frequency to arrange to try a new frequency from the day's subset.

If the NCS determines that the new frequency will work for the whole net, then the new frequency is used for the whole net until it fails on one or more network links. If the NCS determines that the new frequency will not work for the whole net, then aircraft having trouble using the new frequency customarily make do with it. This procedure is followed as long as HF propagation allows communication for all the net members whose participation is critical to a particular mission.

Although the current procedure appears to work acceptably for a considerable proportion of TADIL A operations, it is time-consuming and requires relatively frequent intervention by operators. Furthermore, in operations in the extreme north, where RADIL aircraft often fly, propagation anomalies can make frequency management even more time-consuming and communications less reliable than at midlatitudes. A means for automatic, nearly real-time assessment of channel quality and, possibly, for automatic linking of TADIL A network nodes, is desirable for such network operations.

The existence of a rapidly changing set of useful propagating frequencies suggests that an ALE system will be especially effective for setting up and maintaining TADIL communications in the north. In the simplest implementation of the ALE approach, the ALE system installed in both ground stations and aircraft would be used during TADIL A quiet periods, or during TADIL communications but on other channels, to assess and record the qualities of the assigned channels on a regular basis. Whenever a frequency working for TADIL A communications started to fail, the ALE equipment would be employed to find a new frequency (if one existed) that could be used by the whole net. The information gained in this way would then be used in conjunction with the present voice orderwire (or an orderwire established by ALE) to manually switch net operations to a new frequency.

ALE CAPABILITIES AND FEATURES

The FED-STD-1045/MIL-STD-188-141A automatic link establishment protocol provides a fully automatic system that allows HF stations to periodically sound an assigned set of HF frequencies, measure and store the quality of signaling on each frequency, choose good frequencies, and link to one or more stations on the chosen frequencies [1, 2]. Several thousand ALE modems have been operated according to the standard for the past three or four years, and a large amount of experience and data on their performance has been collected from

midlatitude links. In addition to commercial applications, the modems are used in point-to-point nets by U.S. civil defense and drug enforcement and military organizations, including the Air Force Air Mobility Command.

Generally speaking, ALE provides faster and more reliable connections than conventional manual methods and relieves radio operators of most of the work formerly needed to find useful HF channels and set up and maintain links. Reducing the amount of this work with ALE can increase the amount of time TADIL A nets spend transmitting and receiving surveillance data.

One of at least two ways that an ALE system can improve RADIL TADIL A communications involves using ALE modems for real-time channel evaluation alone. In this approach, TADIL A nodes use their ALE modems independently of their TADIL A modems to assess channel quality as a guide to the choice of appropriate TADIL A network frequencies. This would normally be done by means of ALE net calls from the NCS to the airborne picket nodes. Net calls would establish one or more frequencies that could be used for the entire net. Another more effective approach involves a system controller (additional hardware and software) to coordinate ALE and TADIL operations. We discuss this approach in appendix B.

ANALYTICAL APPROACH

In this report, we assess the general effectiveness of FED-STD-1045/MIL-STD-188-141A ALE as a means for improving HF communications between ground stations and AWACS aircraft flying in the RADIL operating area. In most of the analysis, we assume that ALE and TADIL equipment are coordinated manually. We also assess the likelihood that the 90-percent mission availability that RADIL would like to achieve on TADIL A links—including those in the far north—will actually be achieved.

Because of the lack of sufficient data on both ALE and TADIL A performance in the north, the analytical approach presents first some general probabilistic arguments for the improvement in TADIL A communications that can be expected from the use of ALE. These arguments are based on differences between ALE and conventional techniques and rough predictions of propagation in the north, provided by the Ionospheric Communications Analysis and Prediction Program (IONCAP) propagation prediction program [3]. IONCAP gives MUF and LUF predictions similar to those provided by MINIMUF. (Although MINIMUF and IONCAP will predict the MUF and LUF for northern links, they are not as accurate there as they are for midlatitude links.)

We follow the predictions with a discussion of the available data on both narrowband and wideband propagation and communications in the north and its implications for frequency management in a northern TADIL A network. The data are taken from tests carried out near Iceland and Greenland, in northern Canada, and in northern Europe. These tests were run by

the U.S. Navy, The MITRE Corporation, the Canadian Communications Research Centre, and the Norwegian Defense Research Establishment. The data are used to modify the probabilistic approach so as to more realistically compare ALE operation with conventional operations in actual northern conditions. We also discuss additional data on the performance of an earlier (but similar) ALE system used during tests involving actual patrol flights near Iceland.

CONCLUSIONS

A review of the available data on narrowband and wideband communications performance in Iceland, Canada, and Norway shows that propagation conditions are frequently disturbed in those regions, and that the length of time a channel remains useful for TADIL data transmission is shorter there, on average, than at midlatitudes. Useful channels in the extreme north (above about 70 degrees) sometimes persist, on average, between one-half hour and two hours, whereas midlatitude channels typically persist for five or six hours outside the dawn transition period.

TADIL operations in such conditions may therefore require relatively frequent changes of frequency as one channel fails and other ones become useful. An ALE system can automatically assess the quality of all assigned channels (except possibly the one being used by TADIL) on a regular basis before it becomes necessary to switch to any particular one. This is the ideal way to relieve the TADIL system of the requirement that new channels be determined manually (by means of a voice orderwire) from a small number of channels suggested by the frequency coordinator before each flight.

If the ALE sounding rate is about the rate at which channels fail, then the mission availability will be raised to whatever level is supportable by the state of the ionosphere in the operating region. Determining whether the resulting mission availability will exceed the desired 90-percent level will require data from on-the-air tests of an ALE-assisted TADIL A network operating in northern regions. Data from recent U.S. Navy and Canadian tests of ALE shed some light on this question, but those tests have not provided data on the ALE-TADIL combination.

A 90-percent mission availability is unlikely to be achieved at all times for extreme northern links (where reliability of individual links in the absence of ALE may be as low as 20 percent during periods of ionospheric disturbance, according to Navy, MITRE, and Canadian experiments). However, such low link reliabilities can be raised significantly if channels are sounded with ALE equipment and the channel sounding rate is increased to make the time between updates commensurate with the channel persistency (the average time a particular frequency remains reliable). This will raise TADIL A mission availability. A quantitative, data-supported assessment of how high an ALE system will raise mission availability in RADIL operating areas will require on-the-air tests of ALE-assisted TADIL operations in those areas. Tests of ALE carried out between ground stations have recently been completed

as part of the Canadian experiments referred to above. These experiments should be extended and consideration should be given to additional on-the-air experiments using the already acquired equipment (that is, using both ALE and TADIL A).

We recommend that further data on ALE-assisted TADIL communications be collected using the already acquired equipment. Initially, such data collection can be from operations between ground stations, as in the Canadian tests, but, ultimately, tests in northern regions between ground stations and ALE-equipped aircraft should be carried out. RADIL should consider setting up and gathering additional propagation data from ALE-equipped ground stations in the north even before AWACS aircraft are equipped with the ALE capability. The cost of such stations is relatively small compared with that of equipping an aircraft with ALE, and the stations could be used later for frequency management and propagation prediction in support of ALE-assisted flight communications.

The most efficient operation of a network of ALE-assisted TADIL stations would be facilitated by a system controller at each station that automatically coordinates the operation of the ALE modem and its transceiver with that of the TADIL A modem and its radio(s). We recommend that the development of such a controller (which might become part of the current TADIL A controller) be investigated. In the absence of a system controller, coordination of the ALE and TADIL systems must be performed by an operator at each radio station, but this would still be an improvement over the current approach.

The MITRE tasking did not call for an assessment of the TADIL A system itself. However, differences between the waveforms and error-correction schemes of the ALE and TADIL A modems suggest that there may be times when an ALE modem will link on a channel that the TADIL modem cannot use, or can use for only an unacceptably short time. If tests show this to be the case, it is possible that a more robust data-transmission waveform and signal processing will do better than TADIL A in northern operations. Such waveforms should then be considered. Examples of such waveforms are the serial-tone, PSK-modulated waveform prescribed by MIL-STD-188-110A [4], which is implemented in nondevelopmental item (NDI) modems, and a wideband (1-MHz bandwidth) waveform developed by MITRE. Equipment that implements a wideband waveform is in the advanced stages of development.

The main conclusion of the report is that ALE should offer significant improvement of TADIL A operations in northern regions and that ALE should be implemented in the six ground stations and in the AWACS aircraft that are netted with them.

ALTERNATIVES FOR FURTHER IMPROVEMENTS IN PERFORMANCE

Automatic operation of ALE with the TADIL A system is worth considering but not recommended for installation before more is known about TADIL A performance in the extreme

north. Further improvements could also be realized using a modem with a more robust waveform and signal processing (based on MIL-STD-188-110A) for netted picket operations in northern regions.

Completely automatic operation of a combined ALE-TADIL system would require a system controller. The general layout of a RADIL node that is run by a system controller is shown in figure B-1 in appendix B. In this approach, the ALE and TADIL A modems would be connected via a hardware interface and software in the system controller would control the two modems and the radio(s). The ALE-TADIL System would be installed on the aircraft and at the ground stations. The controller would initiate and control the ALE net call process to establish links from the NCS to the pickets, and the controller would then pass the established links automatically to TADIL A modems.

The system controller software would reside in one of the current TADIL A controllers (if feasible) or in a separate controller dedicated to coordinating the channel-sounding and linking operations of the ALE system (including the radio used for ALE) with the polling and data-transmission operations of the TADIL A system. (Such software and such a system controller do not yet exist.) A more detailed description of the functions of such a controller and its software is given in appendix B.

In appendix C, guidance is given on the choice of data communications equipment using alternative data waveforms and signal processing that can be expected to provide more robust communications in the north than can be achieved using the TADIL A waveform and modems. These alternatives could bring TADIL communications even closer to the 90-percent mission-availability goal.

In appendix D, we include some rough estimates of the cost of implementing a fully automatic ALE-TADIL A system or a fully automatic ALE-robust-modem system for northern nets. We also give brief descriptions and estimated costs of alternative ground-station radio configurations.

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INTRODUCTION

1.1 THE PROBLEM

The Canadian Regional Operations Control Center Airborne Warning and Control System (AWACS) Digital Information Link (RADIL) program has acquired 1-kilowatt, high-frequency (HF) radios and FED-STD-1045/MIL-STD-188-141A automatic link establishment (ALE) modems from the Harris Corporation to equip two ground stations in the northern half of the western hemisphere with the ALE capability. The ground station hubs are located in Edmonton, Alberta, and Debert, Nova Scotia. The AWACS aircraft that will communicate with them will generally be flying in the northern or extreme northern hemisphere. Although the RADIL/Rapidly Deployable Integrated Command and Control System (RADIC) program plans to equip the AWACS aircraft with the ALE capability, no funds have been allocated for this purpose.

Communications in the northern regions, where most RADIL air surveillance takes place, are often affected by poor HF communications caused by auroral and polar ionospheric phenomena. These phenomena arise from the relatively small amount of direct solar illumination experienced in the north, the relatively large amount of particle precipitation that arises in connection with auroras, and the magnetic-field-aligned irregularities (connected with the fact that the magnetic field lines in polar regions are nearly perpendicular to the earth). These phenomena can cause any specific propagating frequencies to be present for shorter periods than corresponding frequencies at midlatitudes. Furthermore, even when frequencies allow propagation in the northern regions, the resulting communications are often poorer than they would be at midlatitudes. The poorer communications may be due to fading, large arrival time variations (delay spreads), and intermittent propagation failures caused by moving field-aligned irregularities and auroral ionization effects.

Thus, the two main properties of these comparatively poor communications are: specific useful frequencies generally last for shorter periods (especially at night), and frequencies that are useful are affected by fading and intermittencies more often than at midlatitudes.

Mission availability is defined as the percentage of time the Tactical Digital Information Link (TADIL) A network is able to pass data with respect to the total time that it is desired to pass data. The Program Office would like to learn to what level(s) mission availability can be raised in northern operations, where propagation conditions generally change more rapidly and are generally poorer than at midlatitudes.

We should keep in mind that since the main purpose of ALE is finding good channels and establishing links on them, rather than maintaining established links, ALE alone cannot necessarily guarantee a high mission availability in poor propagation conditions.

Whether or not successful links will last long enough in northern propagating conditions to allow the successful completion of RADIL missions of variable lengths should be the subject of further study. However, ALE will allow TADIL A networks to more easily find and maintain working channels (if there are any) after a previously working frequency has failed; in this sense, ALE can increase mission availability. We discuss this possibility as part of the main analysis.

There are two basic approaches to using ALE for RADIL TADIL A communications. In the simplest implementation of the ALE approach, in which the ALE system would have no direct interface to the TADIL equipment, an ALE system installed in both ground stations and aircraft would be used during TADIL A quiet periods to assess and record the qualities of the assigned channels on a regular basis. Whenever a frequency (that would subsequently work for TADIL A communications) started to fail, the ALE equipment would find a new frequency (if one existed) that could be used by the whole net. The information gained in this way would then be used in conjunction with the present voice orderwire (or an order-wire established by ALE) to manually switch net operations to a new frequency. The MITRE tasking focuses mainly on this approach.

As an alternative, the ALE equipment could also be used for RADIL communications in conjunction with fully automatic picket-to-hub data communications. In this approach, the ALE and TADIL A modems would be connected via a hardware interface; the software to control the two modems and the radio(s) would be installed in a system controller on the aircraft and at the ground stations. (Such software and system controllers do not yet exist; a discussion of the controller's required functions is given below.) The controller is typically a microcomputer with the power of a personal computer (PC), although now it can be much smaller than a PC. We discuss this alternative (the discussion of which was not part of the direct MITRE tasking) in appendix B, which describes the desired capabilities of an ALE-TADIL system controller.

To determine if the new ALE enhancement should be made operational at the two Canadian locations (and at other ground entry sites) as a means for channel assessment, we have been tasked to learn what benefits can be expected from using ALE for long-haul HF communications by AWACS aircraft flying in northern regions. ALE performance is to be compared with the performance achieved using the current concept of operations for TADIL A communications.

1.2 CURRENT CONCEPT OF OPERATIONS

The current concept of operations for HF data communications with AWACS aircraft starts with predictions of which frequencies will be useful for a particular TADIL A net on a given day. The frequencies (a subset of an assigned set of 10 to 20 frequencies) are determined by a local frequency manager using a combination of standard propagation programs, such as MINIMUF, ADVANCED PROPHET, or the Ionospheric Communications Analysis and

Prediction Program (IONCAP), which produce generally similar results, and short-term measurements of the daily sunspot number obtained from an on-line service, such as that provided by the Air Force Global Weather Center at Offutt AFB in Nebraska. These data are sometimes supplemented with on-line predictions of HF propagation anomalies caused, for example, by auroral and other polar events.

The standard propagation programs give predictions of the maximum usable frequency (MUF) and the lowest usable frequency (LUF) that will be achieved on a link at a given sunspot number on a given day in a given month. The local frequency manager compares his list of assigned frequencies with the daily MUF and LUF and produces a subset of the assigned frequency set that lies between the LUF and MUF. This subset is usually chosen to be as close to the MUF as possible, to take advantage of the generally better propagation at frequencies below but near the MUF.

The subset typically comprises three or four frequencies, usually given in the order of best-to-worst frequency in terms of expected signal-to-noise ratio (SNR) or reliability (the probability that a required SNR will be achieved on a given day). The TADIL A net control station (NCS) tunes its radio appropriately and tries one of the frequencies in the subset. If its poll of the net shows that TADIL A network communications work on the chosen frequency, then that frequency is used for the TADIL A net.

If one of the net members (including the NCS) later finds that the current net frequency has failed, or is beginning to fail, it uses an HF voice orderwire frequency to arrange to try a new frequency from the day's subset. If the new frequency works for the given link and the NCS determines that it will work for the whole net, then the new frequency may be used for the net until it fails on one or more network links. If the NCS determines that the new frequency will not work for the whole net, then the aircraft that is having trouble using the frequency customarily continues to use the old frequency. This procedure is followed as long as HF propagation allows communication for at least the net members that are critical to a particular mission.

Although the procedure appears to work acceptably for a considerable proportion of TADIL A operations, it is time-consuming and requires relatively frequent intervention by operators. Furthermore, in operations in the extreme north, where AWACS aircraft often fly, propagation anomalies can make frequency management even more time-consuming and communications less reliable than at midlatitudes. A means for automatic, nearly real-time assessment of channel quality and, possibly, of automatic linking of TADIL A network nodes, is desirable for such network operations.

1.3 DESCRIPTION OF ALE

The FED-STD-1045/MIL-STD-188-141A automatic link establishment protocol provides a fully automatic system that allows HF stations to periodically sound an assigned set of HF

frequencies, measure and store the quality of signaling on each frequency, choose good frequencies, and link to one or more stations on the chosen frequencies. Several thousand ALE modems have been operating according to the standard for the past three or four years, and a large amount of experience and data on their performance has been collected from links in midlatitudes. Generally speaking, ALE has provided faster and more reliable connections than conventional manual methods and relieved radio operators of most of the work formerly needed to find useful HF channels and set up and maintain links.

As outlined above, an ALE system can improve TADIL A communications in two ways. In the first approach, the ALE modems are used for real-time channel evaluation. TADIL A nodes use their ALE modems independently of their TADIL A modems to assess channel quality as a guide to choosing appropriate TADIL A network frequencies. This would normally be done by means of ALE net calls from the NCS to the airborne picket nodes. Net calls would establish one or more frequencies that could be used for the entire net.

A more complicated, but perhaps more effective, approach is using ALE net calls to actually establish the links from the NCS to the pickets and pass the established links automatically to the TADIL A modems. This would involve writing software to control ALE and TADIL A modems in a coordinated way and some relatively minor wiring changes at each station to set up an interface between the radio, the ALE modem, and the TADIL A modem. A computer and terminal to run the software would probably also be needed.

1.4 ANALYTICAL APPROACH TO PREDICTING ALE PERFORMANCE

In this report, we analyze the effectiveness of equipment built to FED-STD-1045/MIL-STD-188-141A for ALE as a means for improving HF communications between ground stations and AWACS aircraft flying in the RADIL area of operation.

Because the amount of data on both ALE and TADIL A performance in the north is relatively small, the approach is to present first (in section 2) some general probabilistic arguments for the improvement in TADIL A communications that can be expected from using ALE. These arguments are based on logical differences between ALE and conventional techniques, and the approach makes use of propagation predictions provided by IONCAP.

IONCAP gives MUF and LUF predictions that are similar to those provided by other standard programs like MINIMUF, PROPHET, etc. Although MINIMUF, PROPHET, and IONCAP will predict the MUF and LUF for northern links, their accuracy for northern regions is less than that for midlatitude links. In particular, since these programs do not account for the disturbed conditions frequently encountered on links near or above the moving and highly ionized auroral oval, they often produce overly optimistic predictions of communications performance for northern links.

Having compared ALE and conventional linking for "benign" links, we next modify the comparison in light of available data on the persistence of northern links. The comparison is based initially on the assumption that both ALE and the conventional linking approaches use a channel-information update interval of two hours. In the case of IONCAP predictions, this "update" rate is a typical time between computed predictions for a particular day. In the case of ALE, the assumed update rate is the time between actual channel-quality measurements.

With poor channels (in this case, those with persistence significantly shorter than two hours), neither ALE nor the conventional approach can find very reliable links with a two-hour update interval, although ALE still does better than the conventional approach. However, ALE, in conjunction with its off-line, channel-sounding capability, can be used to update channel-quality assessments more frequently than every two hours. If this is done, there is a good chance that the low reliability can be raised significantly (assuming that channels that support TADIL communication exist). This implies that with sufficiently frequent channel-quality updates, ALE can find channels more quickly and efficiently than the current approach; therefore, ALE should be used.

1.5 ORGANIZATION OF THE REPORT

The analytic comparison is followed in section 3 by a general discussion of the available data on narrowband propagation and communications in the north and their implications for frequency management in a northern TADIL A network. The data (some of which was used in the comparisons in section 2) is taken from tests carried out near Iceland and Greenland, in northern Canada, and in northern Europe. The northern links referred to in the report are shown on the map in figure 1. One of the data sets is of particular relevance to this task since it involves a comparison of performance of an earlier ALE system with the conventional approach.

In section 4, we provide some guidelines when choosing data waveforms and modems that might provide more robust communications in the north than the TADIL A waveform and modems. In appendix D, we include some estimates of the cost of implementing a fully automatic ALE-TADIL A system or a fully automatic ALE-robust-modem system for northern nets. Our conclusions and recommendations are included in section 5.

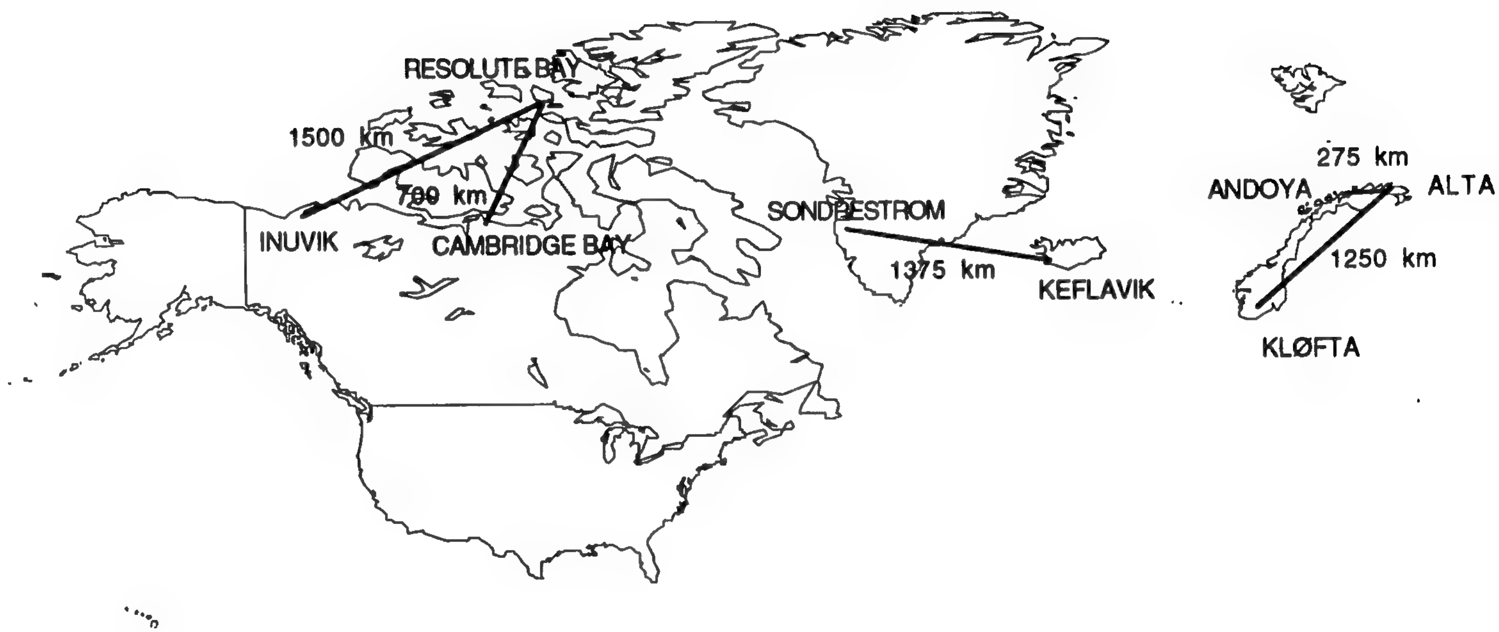

Figure 1. Locations of the Northern Test Links

SECTION 2

PROBABILISTIC ARGUMENTS FOR THE USE OF ALE

2.1 LINK RELIABILITY WITH ALE VERSUS LINK RELIABILITY WITH THE CURRENT APPROACH

The IONCAP defines reliability of an HF link as the probability that a required SNR will be achieved on a particular day at a given time. Because of the randomness of actual SNRs, HF link reliability is never 100 percent (there is always some chance that fading, absorption, or an ionospheric disturbance will lower the SNR below the required value). The network designer's task is to assure that the reliability is high enough to meet user requirements. The RADIL/RADIC requirement of a 90-percent "mission availability" may be expressed in terms of HF link reliability by saying that the reliability of all links in a TADIL A network should be "high" at least 90 percent of the time. We will interpret a high reliability to mean 90 percent.

2.2 LINK RELIABILITY COMPARISON IN BENIGN CONDITIONS

In benign channel conditions, such as those normally encountered at midlatitudes (outside the night-to-day transition period), the persistence of channels with high reliability is usually several hours, a fact confirmed during AWACS operations. In this case, the improvement over the conventional frequency management approach provided ALE can be assessed by a straightforward probabilistic comparison.

Before we describe the comparison, we give an idea of what the structure of a benign propagating channel looks like and how that structure changes in the course of time. This picture (for a midlatitude link) will be contrasted with a similar series taken from a northern path of similar length and orientation, where RADIL operations take place.

The HF communication signals are normally refracted (bent) from the ionosphere in getting from a transmitter to a receiver. An ionogram, a real-time snapshot of the state of the ionosphere at a particular time, is obtained by sweeping a transmitter and a synchronized receiver across the HF band. Ionograms give some idea of the type and quality of HF communications that can be expected between sites used to generate the ionograms. In particular, they show which parts of the ionosphere are capable of refracting radio waves at any HF frequency at a particular time.

Figure 2 shows an idealized sketch of an ionogram for a typical 1500-km link. The ordinate on the sketch gives the time it takes a signal at a particular frequency to travel from the transmitter to the receiver. The recorded arrival times exhibit typical structures on the ionogram that help characterize good channels and poor ones. The result will be that the

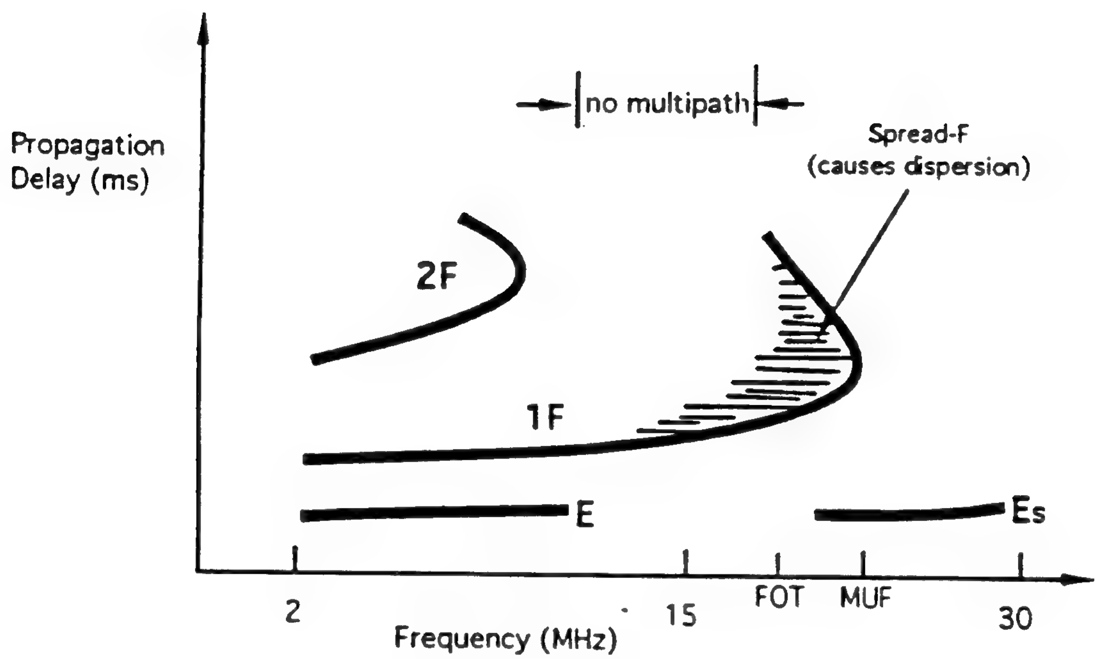

Figure 2. A Typical Ionogram for a Benign Link

channels used sometimes by TADIL A in the north are sometimes very poor on the basis of the corresponding ionograms. The 1F-layer shown on the idealized sketch is the layer normally used for HF communications during the day. The place where it turns back on itself is the so-called MUF.

The best frequencies for communications are usually about 85 percent of the MUF, and the best radio paths are usually those that have one hop via the F-layer (1F returns). When 2F signal returns occur at the same time and frequency as 1F returns, they can result in multipath and high TADIL A bit error rates (BERs). "Fuzzy" or thick traces corresponding to the F-layer or E-layer also indicate the possibility of multipath and fading. The E-layer returns shown on the sketch can sometimes be used for communications if the E-layer refracts strongly enough. At other times, the E-layer obscures the F-layer, which can also lead to poor TADIL A communications. Poor data communications with TADIL A can also be expected when the general shapes of ionograms are changing rapidly—for instance, more rapidly than once every few hours.

Figures A-1a through A-1e in appendix A show actual ionograms for an HF path between Illinois and Massachusetts. The series covers about an hour-and-a-half and has the general "benign" appearance of most other ionograms that might be taken during the daytime on this link. In the absence of strong interference from signals outside the net, or strong local noise, TADIL A communications could be carried out on frequencies in this range for several hours before a change of frequency would be necessary. This series may be compared with another series (discussed in more detail below) taken from a poor link near Greenland, in a region close to the auroral oval typical of RADIL operations. The second series has generally fuzzy structure; furthermore, its structure is changing rapidly.

We now analyze what might be expected during TADIL operations over such benign and poor links. We pursue the analysis from the standpoint of how ALE will perform in finding reliable channels compared with the conventional (manual) approach to choosing channels. We start by assuming that both ALE and the conventional linking approach use channel-quality information that is updated not more often than every two hours. (For example, in the case of the conventional approach, an update is a new set of IONCAP predictions.)

In appendix E, we derive expressions for the probability of finding a reliable channel on a particular attempt with ALE and the conventional approach. The derivation assumes that the reliabilities used in the analysis are accurate. The derivation is based on the idea that since ALE will automatically try all the assigned channels on a particular linking attempt (if necessary), it is inherently more efficient than the conventional approach, which tries only the predicted best frequency on any attempt (a failed conventional attempt generally requires an orderwire arrangement for another attempt).

To compare the reliabilities of the conventional frequency management method and the ALE approach in benign northern conditions (channel persistence no shorter than two hours), we ran IONCAP for two northern links: a 700-km link from Cambridge Bay, Northwest

Territories (NWT), Canada, to Resolute Bay, NWT, and a 1400-km link from Söndreström AFB, Greenland, to Keflavik, Iceland. Each link was run around the clock for times separated by two hours. Data on actual persistence of the two links will be used below to modify the benign results to account for sometimes worse conditions.

The Canadian link is a northern one for which actual data on link persistence and best propagating frequencies have recently been collected over a year-and-a-half by G. Nourry and his colleagues at the Communications Research Centre (CRC) in Ottawa, Canada [5]. Nourry, in fact, used a FED-STD-1045 modem to determine which frequencies were propagating on each link and for how long. The Resolute Bay station at 75 °N is usually above the auroral oval (which normally lies between about 65 and 75 degrees north latitude), and Cambridge Bay at 69 °N is frequently above it (refer to figure 1), so one would expect this link to be affected by poor polar propagation conditions quite often.

The Greenland-to-Iceland link is one for which detailed ionogram and BER data for a wide-band HF system were collected over a two-month period early in 1992 as part of experiments in which MITRE participated [6, 7]. The Söndreström station at 68 °N is often above the auroral oval, so this link is often affected by northern propagation phenomena. In fact, the data for this link were collected during a time of rather poor propagation conditions (frequent spread-F, rapidly changing ionograms, large delay spreads, and a sometimes rapidly changing channel-scattering function). Ionograms that bear on actual performance on the Greenland link will be discussed in the next section. Since we assume benign conditions to begin with (as might be expected by a user of propagation programs alone), we suppose, as mentioned above, that the reliability predictions remain valid for at least as long as the two-hour interval between predictions for both links.

The Canadian link was analyzed for April 1990, assuming a sunspot number of 120, a transmitter output power of 400 watts (the aircraft's nominal output), and antennas with -6 dB gain, which is typical of airborne antennas. The date and sunspot number correspond roughly to those of the Canadian measurements. The arbitrarily but reasonably chosen frequencies for the run were 6.1, 7.5, 10, 12, 14, 17, 20, and 25 MHz.

Figure 3 shows a graph of the reliability in benign conditions, with values plotted every two hours, for this link as a function of Greenwich mean time (GMT) for two linking approaches, using ALE and the conventional approach. Since ALE can potentially try all the assigned frequencies, its reliability in figure 3 is given in Eq. (1) in appendix E. Since the conventional, prediction-based approach will try the predicted best frequency, its reliability in the figure is given by Eq. (2) in that appendix.

The points on the graph in figure 3 are connected by straight lines to make it easier to read. With the exception of one time point (16:00 GMT), when possible D-layer absorption lowered the reliability of all propagating frequencies significantly, ALE kept the predicted link reliability near one, which was, on average, about 10 percent better performance than with the conventional approach.

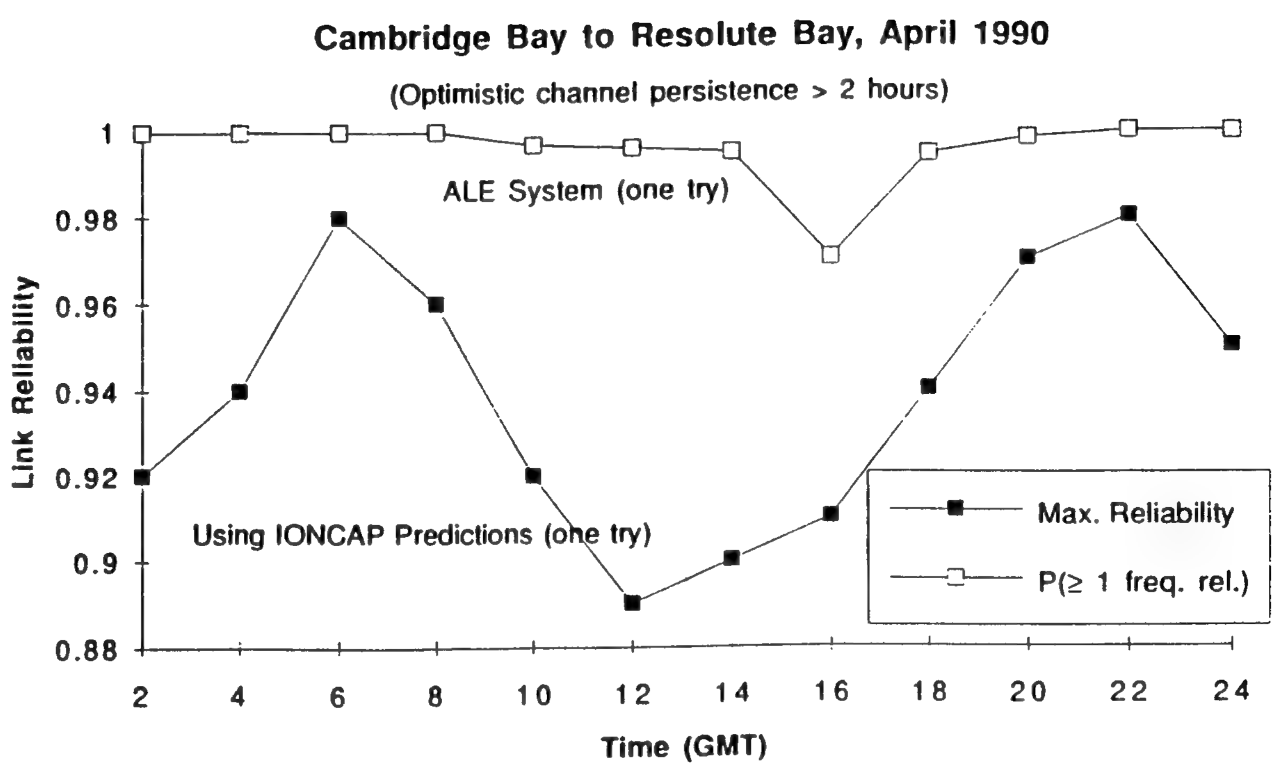

Figure 3. Link Reliability in Benign Conditions, Cambridge Bay to Resolute Bay, NWT

This reflects the fact that in this case ALE has eight chances to find a reliable link (even though some of the eight frequencies are unlikely to be reliable), whereas with the conventional approach there is only one chance on each linking attempt.

Of course, under the traditional approach, users can try a second frequency if network linking on the predicted "best" frequency fails. But this will normally have to be arranged over the voice orderwire and will take much longer than with ALE, which will, if necessary, automatically try all the assigned frequencies in the order of their recently measured quality in a matter of a minute or two.

The generally high reliabilities with both approaches are consequences of two assumptions: that the link is benign, and that prediction programs like IONCAP (which are the basis of the current linking approach) accurately reflect propagation in the north. These assumptions are not always valid for northern RADIL links.

Since the most reliable frequencies for this relatively short link would normally lie in the lower half of the HF band, one would not expect these results to differ much from the case in which only four frequencies made up the assigned set. A review of the reliabilities predicted by IONCAP for this link shows this to be the case (the highest four frequencies: 14, 17, 20, and 25 MHz) usually have such low reliability for this link that their reliabilities have little effect on the comparison between the ALE and conventional approaches.

The Greenland-to-Iceland link under benign conditions was analyzed for March 1992, assuming a sunspot number of 105. This corresponds to the date and sunspot number for the actual measurements. The frequencies, output power, and antenna gain are the same as for the Canadian runs. Figure 4 shows the ALE and conventional-method reliabilities for this link in benign persistency conditions (persistency > 2 hours). In this case, ALE, assuming benign conditions, yields a reliability near one except during a brief period of increased absorption at noon; this is about 25 percent greater than the reliability with the conventional approach. During the period of increased absorption, ALE yields a reliability about twice that of the conventional approach.

The relatively high reliabilities achieved for ALE, and the poorer, but perhaps still acceptable results achieved for the conventional approach, correspond to air crew experience at midlatitudes, where channel persistence is typically high and one or more useful frequencies can usually be found. In this case, the main advantage of ALE lies in its ability to free operators from having to find useful frequencies with manual methods using the voice orderwire. These high reliabilities do not always correspond to air crew experience in northern regions, however, where channels often change much more rapidly and have lower quality than at midlatitudes. In the following paragraphs, we discuss the advantages of ALE in the generally poorer propagation conditions encountered in northern operations.

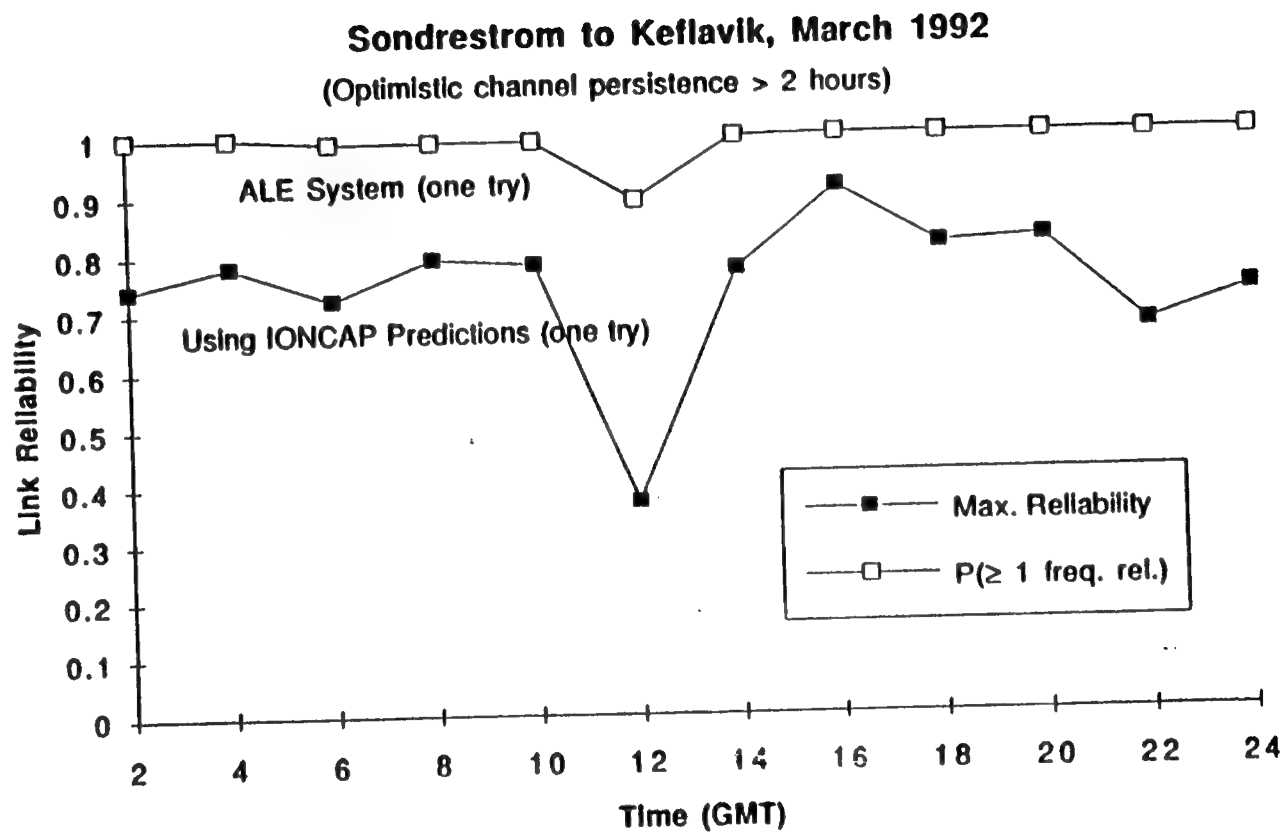

Figure 4. Link Reliability in Benign Conditions, Sondrestrom to Keflavik

2.3 TYPICAL NORTHERN CONDITIONS

To get an idea of how ALE compares with conventional frequency management for a typical (that is, more frequently disturbed) northern link, we modified the comparison of the previous section to account for a shorter channel persistency on the two links referred to above. For the Canadian link, the modification uses data on the Cambridge Bay-Resolute Bay link collected by Nourry and his colleagues. The Nourry data show that the best propagating channels for this link (around 7 MHz) persist on average for about 50 minutes (as opposed to the persistence of at least the two hours we assumed in the previous section). Nourry found that the channels far away from 7 MHz persist, on average, for only about 30 minutes.

To modify the previous results to account for the measured persistency on this link, we argue that the reliability at two-hour intervals of a particular channel for this link is actually the product of the predicted reliability and the ratio of the persistency to the interval between predictions (50 minutes/120 minutes ≈ 0.4); that is, the reliability at a particular time has to be lowered by the probability that the channel in question is still propagating. For channels away from the most reliable ones, which still have a small chance of producing a sufficient SNR, this modification is somewhat optimistic, since the persistence of these channels is lower than 50 minutes. But lowering the reliability of all channels to 40 percent of its value in benign conditions will give us a good idea of what to expect in actual operating conditions. (The fact that some of the assigned frequencies we chose have very low reliability shows the importance of proper frequency management. If the entire set of frequencies tried by ALE or the conventional method is not suited to the length of the links or the time of day, linking (and TADIL) results can be much poorer than predicted with either method.)

Figure 5 compares ALE to conventional link establishment for the Cambridge Bay-Resolute Bay link under the same average propagating conditions as before, but with all reliabilities lowered to 40 percent to account for measured persistence. The chance of finding a reliable channel that lasts for two hours is now about 40 percent with ALE and slightly lower with the conventional approach.

The most important conclusion to be drawn from the Cambridge Bay results is that in typical northern conditions, reliable channels may persist for much shorter periods than at midlatitudes. When this happens, an ALE system's ability to sound the assigned channels can be used to automatically determine which frequencies should be tried after a reliable channel starts to fail. If the sounding is performed at about the same rate as channels are failing and other reliable channels exist, then the ALE sounding will find them. ALE, therefore, offers the potential for raising TADIL A throughput considerably in poor propagation conditions.

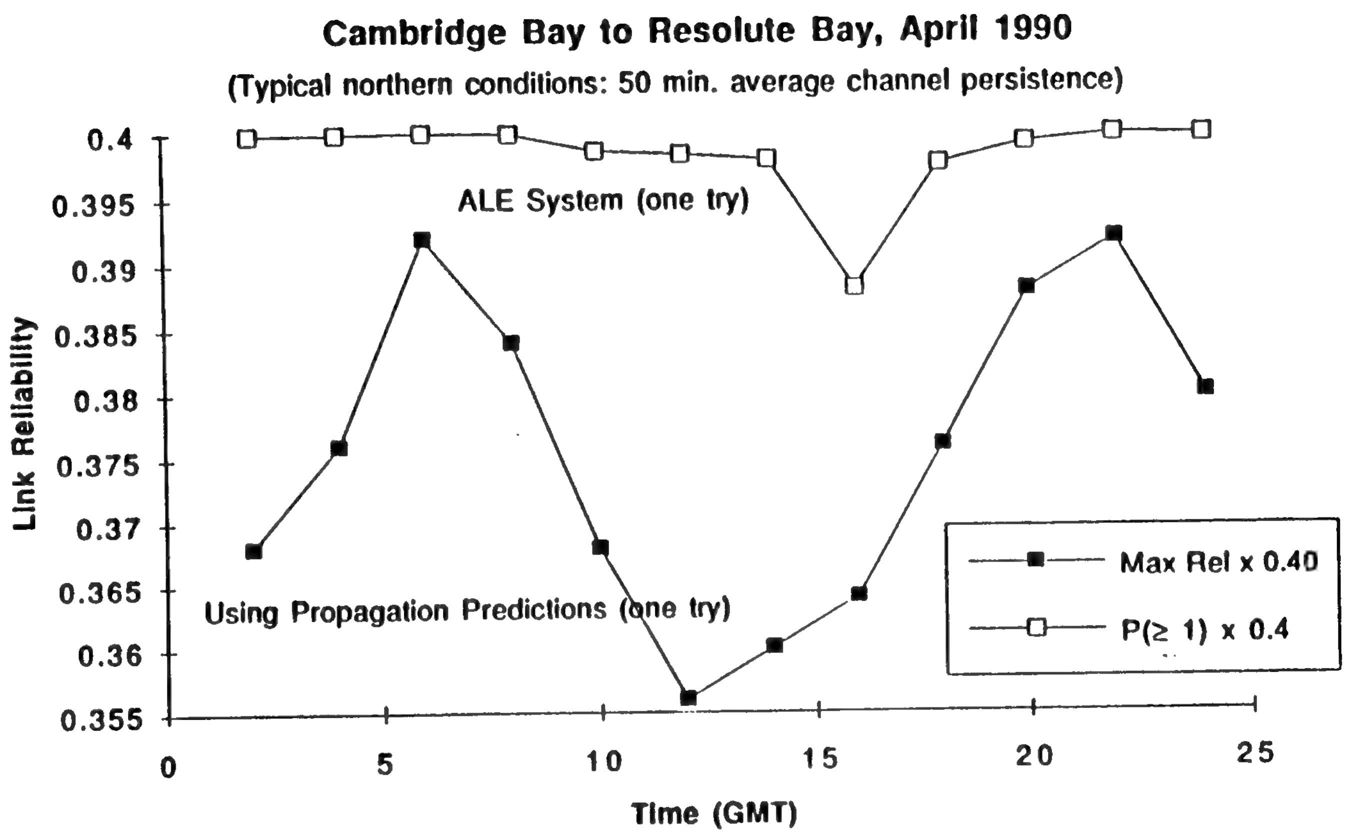

Figure 5. Link Reliability in Typical Northern Conditions, Cambridge Bay to Resolute Bay, NWT

2.4 POOR NORTHERN CONDITIONS

In the remaining paragraphs, we compare ALE with the conventional approach for the Greenland link discussed above, and for a Resolute Bay-to-Inuvik link, monitored by Nourry and his colleagues, in the Canadian Northwest Territories (refer to figure 1). The Greenland link demonstrated relatively poor communications performance during most of the two-month testing period. Spread-F, "slant-F" (probably caused by magnetically induced "tilts" in the F-layer and observed on ionograms collected for this link), and large delay spreads (causing bursts of bit errors during wideband HF communication) were frequently observed during the tests. Although ionograms were not available for the Resolute Bay-to-Inuvik link, this link was monitored for much longer (about a year-and-a-half) than the Greenland link. The Resolute Bay-Inuvik link, which usually lies above the auroral oval, also showed poor communications performance in terms of markedly short channel persistence (see below).

With respect to the Greenland link, the communications performance of a wideband system (and especially of a prototype, as in this case) cannot be compared directly with that of narrowband systems like TADIL A and ALE. However, data collected during the MITRE experiments on channel characteristics (channel Doppler spread and delay spread, and their product, the channel "spread factor") can give some insight into what can be expected from the performance of a narrowband system in such conditions. In particular, such data can give a fairly clear picture of how fast the quality of a narrowband channel can be expected to change.

Figures A-2a through A-2f in appendix A show a series of (narrowband) ionograms taken for the Greenland link. The series corresponds to the same local time as the ionogram series taken for the benign link discussed in paragraph 2.2. The Greenland link has about the same orientation and length as the benign link. The differences between this series and the benign one are striking. Although the two series show roughly the same MUFs, the Greenland series is uniformly more diffuse than the benign series. The 1F trace is filled with returns that suggest that there is no sharply defined edge of the F-layer for this link: radio signals will be "smeared" in terms of arrival time at a receiver, which will cause inter-symbol interference at the demodulator input and high BERs for TADIL communications.

There are also diffuse 2F signal returns, and it is often difficult to separate them from 1F returns, which would also lead to smearing of received TADIL signals. In the third and fourth ionograms are "plumes" associated with "slant-F" phenomena connected with "tilts" in the F-layer. Slant-F returns can cause severe delay distortion of narrowband signals, such as those used with TADIL A.

This series is typical of other ionograms taken for this link during these experiments, and it gives an idea of the differences between propagation in the north and at midlatitudes.

Figures 6 and 7 show simulations of the position of the visual auroral oval at midnight and noon, eastern standard time (EST). (The position of the visual oval is a reasonably good general predictor of the oval's electromagnetic effect on HF communications.) Superimposed on the figures is the position of the link between Söndreström AFB and Keflavik. You can see that the electromagnetically active part of the oval passes near the mid-point of this path at 00:00 EST and is far away from it 12 hours later. The proximity of the oval to this path and the rate at which it moves across the link (about 200 km/h) are consistent with the generally poor HF communications experienced on this link.

To learn how propagation like that shown in the ionograms might affect ALE and TADIL operations, we have studied data on Doppler spread and delay spread taken for this link. The product of the delay spread and Doppler spread (the "spread factor" for the channel) is a characterization of how well the channel will support digital communications: a small spread factor (not much change in signal delay and in carrier frequency) with sufficient SNR will support digital communications; a large spread factor (large Doppler spread or delay spread or both), even with a sufficient SNR, may not support communications.

If the spread factor rises significantly and stays high, TADIL operations may fail, and ALE (with updated sounding data) may be able to find a usable new channel. The rate at which the spread factor changes significantly (doubling, for instance, or falling by half) is a good indication of how often the quality of a narrowband link might change significantly. In the case of TADIL communications, a significant change in link quality often calls for a change in operating frequency. Without ALE, this would have to be done by arrangement over the voice orderwire. With ALE, it would be done automatically, with a net call, for example.

Keep in mind that a poor enough channel may also prevent ALE from working (despite its relatively robust waveform and coding), and that a channel found by ALE, which currently bases channel quality essentially on SNR measurements, is not necessarily good enough for long-term TADIL A communications.

A preliminary look at the wideband data from the Greenland link suggests that for this link the spread factor changed significantly every 5 to 30 minutes during this experimental period. Although this observation is far from characterizing operations in the north, it suggests at least what might be expected in poor conditions there.

If we assume (for comparison purposes) that a northern disturbed channel has a persistence of 25 minutes, we can compare ALE (with a two-hour, channel-measurement interval) with conventional link establishment in an example of a disturbed northern channel. This is done by simply multiplying the reliabilities predicted for ALE and conventional link establishment by 0.20 ($\approx$ 25 minutes/120 minutes). The result is shown in figure 8. The reliability with ALE has fallen from values near one to reliabilities of about 20 percent. Without ALE, the reliability is about 15 percent. The slight dip in both curves at 12:00 GMT is probably due to

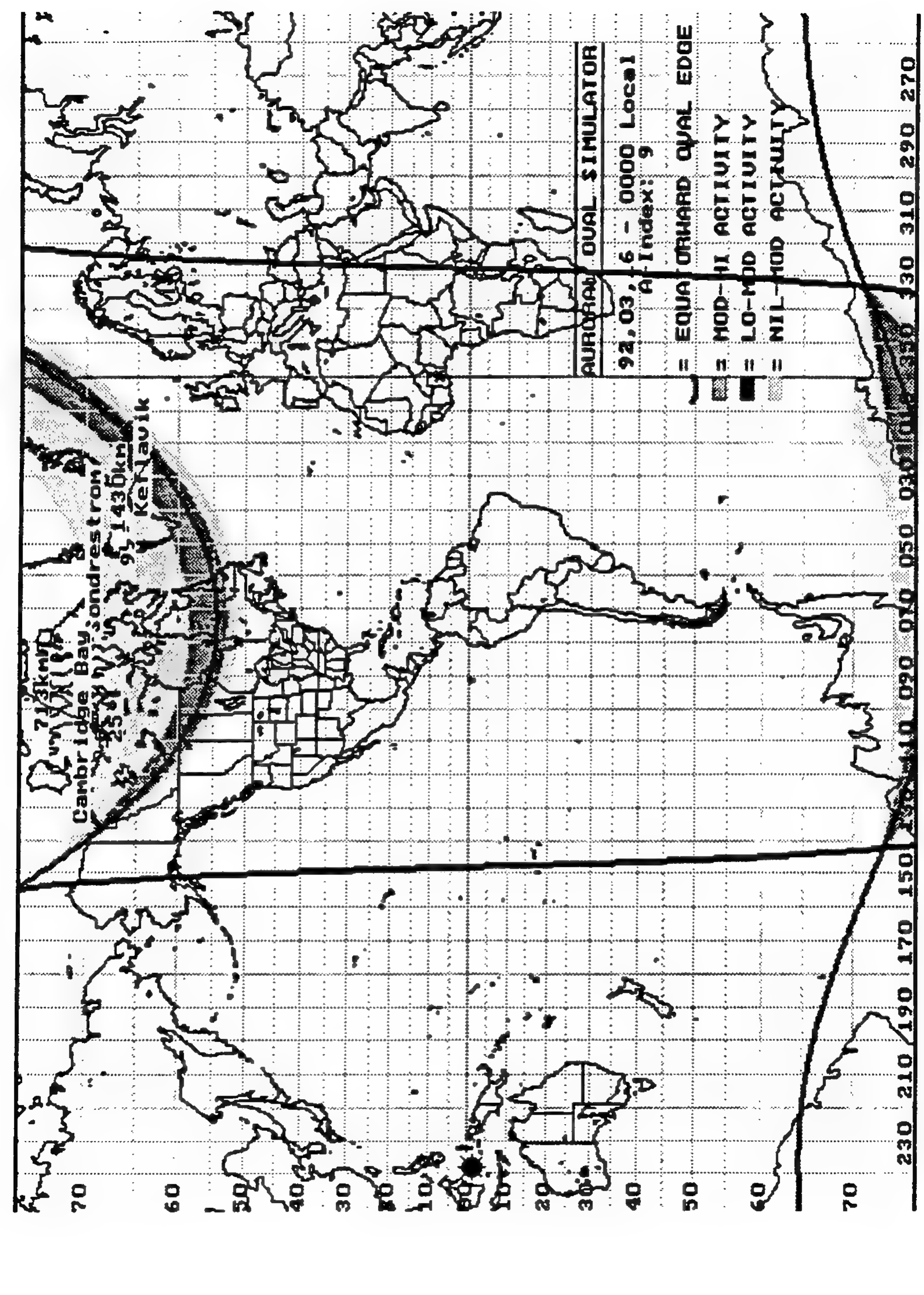

Figure 6. Position of the Auroral Oval at 0000 EST

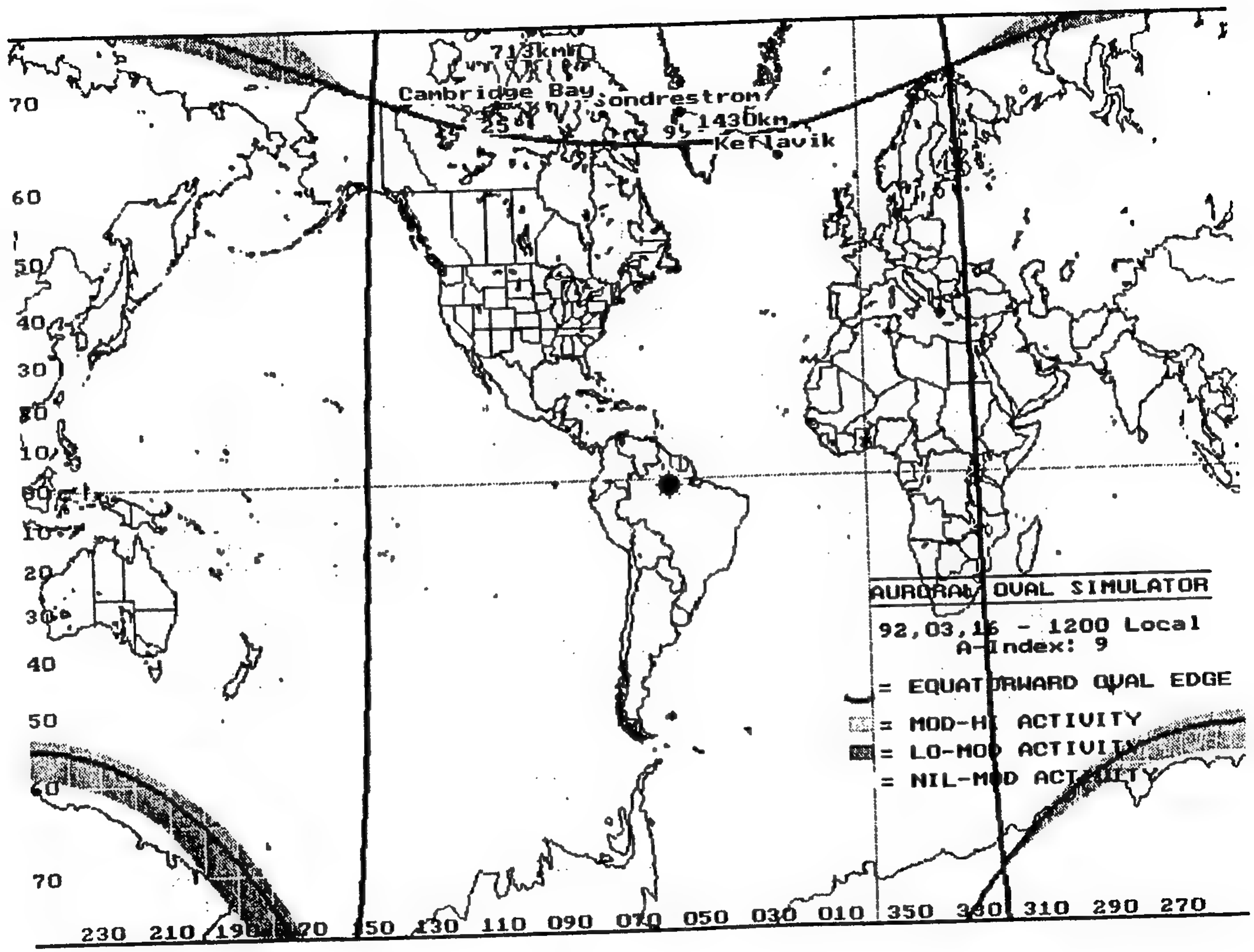

Figure 7. Position of the Auroral Oval at 1200 EST

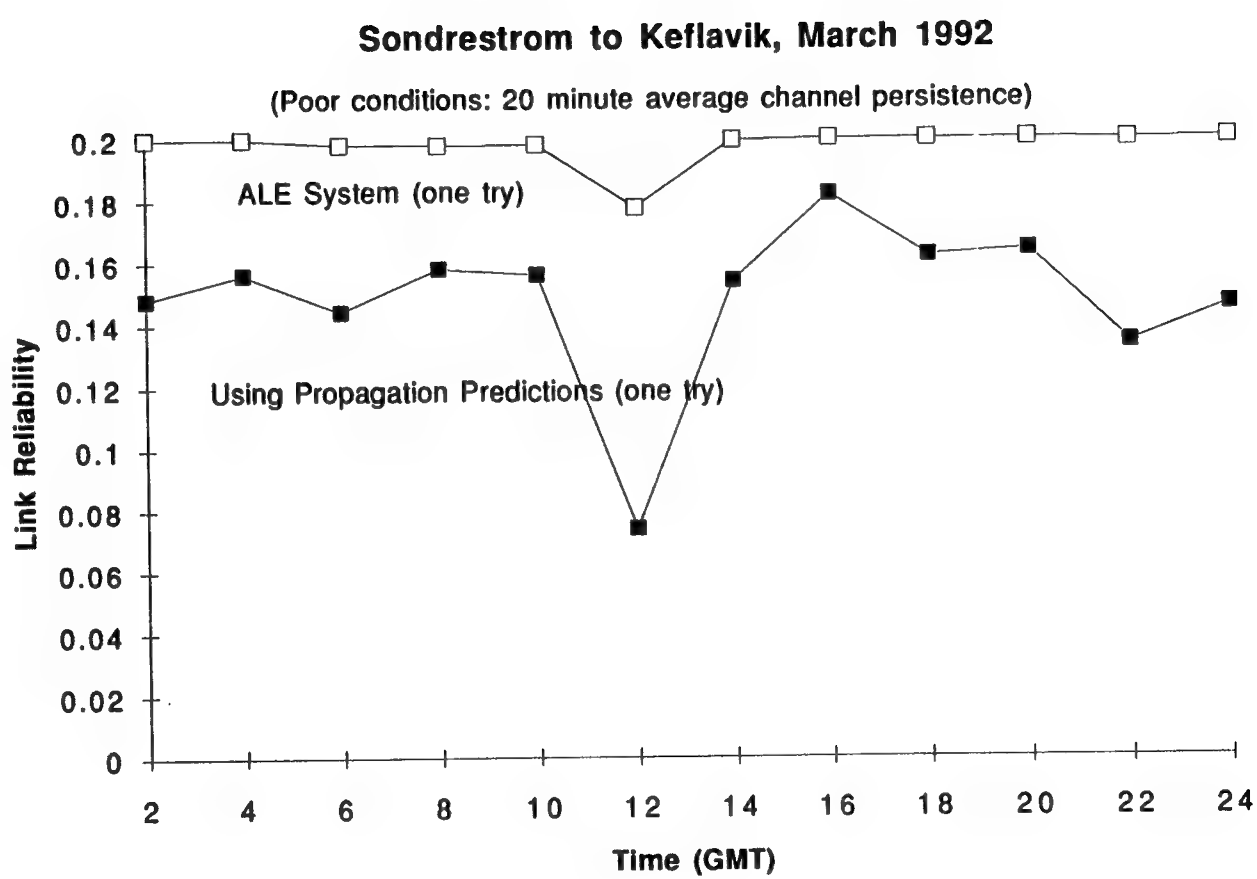

Figure 8. Link Reliability in Poor Northern Conditions, Sondrestrom to Keflavik

D-layer absorption. This is a case in which ALE sounding conducted independently by radios not involved with TADIL communications could possibly be used to find new channels.

The soundings would have to be performed with an update about as frequently as the rate at which the channel is changing, namely once every half-hour or so in this case. Of course, it cannot be guaranteed that channels found by means of the frequent soundings would support communications in disturbed northern conditions. It might be necessary to use a more robust waveform (such as a wideband spread-spectrum one with a channel-compensating Rake modem) to cope with channels having large spread factors. On-the-air testing is the best way to determine the performance of a more robust waveform relative to that of the TADIL A modem.

Recently acquired data from the Canadian link between Resolute Bay and Inuvik in the Northwest Territories show that this narrowband link has an average persistence on 15 frequencies between 3 and 25 MHz of only about 23 minutes. This is consistent with the Navy/MITRE wideband measurements of the rate of change of the channel spread factor.

SECTION 3

PROPAGATION PREDICTIONS VERSUS MEASURED COMMUNICATIONS PERFORMANCE OVER NORTHERN LINKS

In this section, we discuss three recent comparisons of measured HF communications performance in northern regions with predictions using IONCAP and PROPHET, two widely accepted standards. Such comparisons suggest how conventional link establishment techniques based on such predictions will perform relative to ALE, which can be expected (with an appropriate sounding schedule) to find the channels corresponding to measured performance.

The comparisons show that predictions and measured performance differ significantly in northern regions and that ALE does much better than the conventional approach. This contrasts the general experience at midlatitudes, where predicted and measured values of good operating frequencies and performance on such frequencies are in rough agreement. (We should bear in mind that the comparisons in section 2, which were based on IONCAP predictions, concerned the relative advantages of ALE and conventional linking in northern regions and not the accuracy of IONCAP predictions in such regions.)

The first set of comparisons [8] was for a pair of ground links in the northern half of Norway. One link was short (275 km) and its reflection point lay within the auroral zone. The other link was longer (1230 km) with its northern part in the auroral zone but its reflection point outside the zone. Communications over these links were compared with IONCAP predictions.

The second set was for four links in northern Canada monitored by G. Nourry and his colleagues between 1990 and 1992 [5]. Nourry used MIL-STD-188-141A modems to determine which of 15 programmed frequencies were usable on each link and for how long. His published results to date are limited to plots of usable frequencies and channel persistence averaged over all times of the day for the entire year-and-a-half measurement period. Nourry's experiments are directly relevant to RADIL operations, since the experiments were actually designed to assess the extent to which the ALE systems improve upon conventional channel tuning and linking techniques in northern operations.

The third set was for links attempted during several flights of a U.S. Navy P-3C patrol aircraft between itself and a ground station in Keflavik, Iceland [9]. The flights took place to the northeast of Keflavik. The tests involved links attempted using the conventional approach assisted by PROPHET and ALE using a modem employing the Rockwell-Collins Selscan™ ALE scheme. Selscan uses a somewhat less robust forerunner of the MIL-STD-188-141A waveform, error control, and protocol, but is functionally similar to the newer system. Selscan performance is therefore likely to be somewhat poorer than performance using a modem operating in accordance with MIL-STD-188-141A.

3.1 NORWEGIAN EXPERIMENTS

These experiments, which are apparently ongoing, started in 1987 with a year's worth of data collection on a 275-km path between Andoya (69 °N) and Alta (70 °N) in northern Norway. In July 1989, a similar experiment was started over a 1230-km link between Kløfta (60 °N) and Alta. Nine frequencies for each link were evaluated with an oblique sounder once an hour around the clock. In addition to the sounder evaluation (which allows direct comparison of measured and predicted MUFs and optimal working frequencies (FOTs)), a standard binary data message was sent on each frequency each hour using unprotected FSK, and the bit errors in the message were counted.

The "availability" of a frequency during an hour over an entire month was defined as the percentage of messages sent (at that hour during the month) with a BER less than 10 percent. This availability was then compared with the reliability predicted by IONCAP for each link. (Recall that IONCAP's reliability was defined as the probability that a required SNR will be achieved on a given link at (1) a particular time, (2) sunspot number, and (3) in a given season.) The required SNR (55 dB in a 1-Hz noise bandwidth) was taken to correspond to the accepted requirement for "good quality of . . . radioteletype services." Although under this definition the measured availability is not directly comparable with the IONCAP reliability, the two quantities do allow us to get a general idea of how measured digital communications compare with predictions.

The Norwegian data show that for these two links under the corresponding environmental conditions, the IONCAP predictions are too optimistic, particularly for the shorter link within the auroral region. From the sounder plots, from the shapes of the availability plots and IONCAP reliability plots, and from the measured SNR values for the links, the Norwegian investigators concluded, among other things, that:

- The MUF on the short path at noon (about 6 MHz) was about 6 MHz lower than the IONCAP prediction.
- The predicted MUFs on the short path were too large.
- The absorption on the short path in the morning hours was not predicted by IONCAP.
- With the exception of predicted absorption that was too small during the morning hours, IONCAP's MUF and reliability predictions (to the extent that reliability relates to measured availability) were close to measured values for the long path.

Thus, while the predictions for the long path (whose "reflection" point usually lies below the auroral region) were generally good, those for the short, auroral path were not a very good guide to measured performance in terms of both usable frequencies and communications performance on usable frequencies.

These researchers also found that on days when the ionosphere was "disturbed," measured availabilities were higher than those predicted at night and lower than those predicted during the day. This agrees with observations made by AWACS crews, who report that communications in the north are sometimes especially poor during summer days, when the northern ionosphere is highly ionized and, therefore, likely to be highly disturbed.

The Norwegian data led to the conclusion that TADIL communications in the north for both short and long links, based on conventional (prediction-directed) linking procedures, can be significantly improved by using an ALE system.

3.2 CANADIAN CRC EXPERIMENTS

These experiments, started by the CRC in 1990 and ongoing, involve data collection on fifteen frequencies from the six links of a four-node network of stations in Canada's Northwest Territories (refer to figure 1). The northernmost station (Resolute Bay, 75 °N) is usually above the auroral oval. Two stations (Inuvik, 68 °N and Cambridge Bay, 69 °N) are sometimes above it. The fourth station (Yellowknife, 62 °N) is usually just below the oval. One purpose of the experiments is to evaluate the performance of ALE and robust data modems over polar cap circuits, so that the data collected from the experiments bear directly on RADIL performance.

The data provided to us by the CRC concern: (1) ALE results between Resolute Bay and the other three stations to the south of it, (2) the frequencies that propagate, (3) the best propagating frequencies, and (4) the persistence of propagating frequencies. The data available summarize these measurements over all times and seasons.

3.2.1 Propagating Frequencies

The Canadian data show that propagating frequencies for the Resolute Bay-Cambridge Bay link (700 km, north-south) were between 3 and 10 MHz. The IONCAP runs for this link under average conditions for this period (sunspot number 120) for January, April, and August showed a MUF no greater than 9.6 MHz and an FOT no greater than 7.6 MHz.

The usable propagating frequencies for the Resolute Bay-Inuvik link (1500 km, east-west) were 4.5 to 16 MHz. The corresponding IONCAP predictions (starting with eight frequencies spread across the band from 6 to 25 MHz) for average conditions and the same three months showed a MUF no greater than 14.8 MHz and a FOT no greater than 12.9 MHz.

For Resolute Bay to Yellowknife (1600 km, north-south), the propagating frequencies were 5 to 19 MHz. The IONCAP showed a MUF no greater than 16.4 MHz and a FOT no greater than 11.8 MHz.

These data suggest that there were times when frequencies above the predicted MUF and several megahertz above the predicted FOT would have allowed linking and TADIL communications on the Canadian links. This contrasts with the short Norwegian link referred to above, for which IONCAP significantly overestimated the MUF and, hence, the set of propagating frequencies.

3.2.2 Best Propagating Frequencies

The best propagating frequencies for each link (highest SNR) were near 6, 9, and 16 MHz for the links between Resolute Bay and Cambridge Bay, Inuvik, and Yellowknife. The best frequencies that IONCAP predicted (those with the highest SNR, usually the FOT) were 4 to 6 MHz, 6 to 10 MHz, and 6 to 12 MHz. IONCAP brackets the best frequencies for the first two links but fails to predict the best frequency for the Yellowknife-Resolute Bay link by about 4 MHz.

3.2.3 Number of Simultaneously Propagating Frequencies

The available data pertain to the links from Resolute Bay-Inuvik and Resolute Bay-Cambridge Bay. A frequency was said to be propagating if the ALE modems were able to establish a link on the frequency at the scheduled time. For the Inuvik link, which frequently lies above the auroral oval (where communications are likely to be poor), only about two frequencies propagated simultaneously, on average. Six to ten frequencies propagated at the same time from Resolute Bay-Cambridge Bay.

Using the arbitrary but reasonable criterion that frequencies with reliabilities greater than 50 percent will propagate simultaneously, we find that the IONCAP predicts about five to seven simultaneous frequencies, on average, for the Resolute Bay-Inuvik link. In order to compare the measured and predicted numbers simultaneously propagated in more detail, we calculated the percentage of the total number of measured and predicted instances that a given number of frequencies propagated simultaneously. In the case of the IONCAP predictions, which we ran for two-hour intervals for three seasons (represented by January, April, and August), we took the total number of instances to be the total number of output points from the IONCAP runs (12 time points x 3 seasons = 36 instances).

The comparison for Inuvik is shown in figure 9, where the measured distribution of the number of propagating frequencies is skewed toward zero, whereas the predicted number has a clear mean of about five frequencies. Although comparison in this case depends somewhat on the number and placement of the frequencies input to IONCAP, the comparison nevertheless makes a believable case for the observation that IONCAP may be seriously overestimating the number of simultaneous frequencies for this link.

For the Resolute Bay-Cambridge Bay link, IONCAP predicts between two and four simultaneous propagating frequencies, with propagation again defined as having a reliability greater than 50 percent. As mentioned above, the measured results show that this link actually had

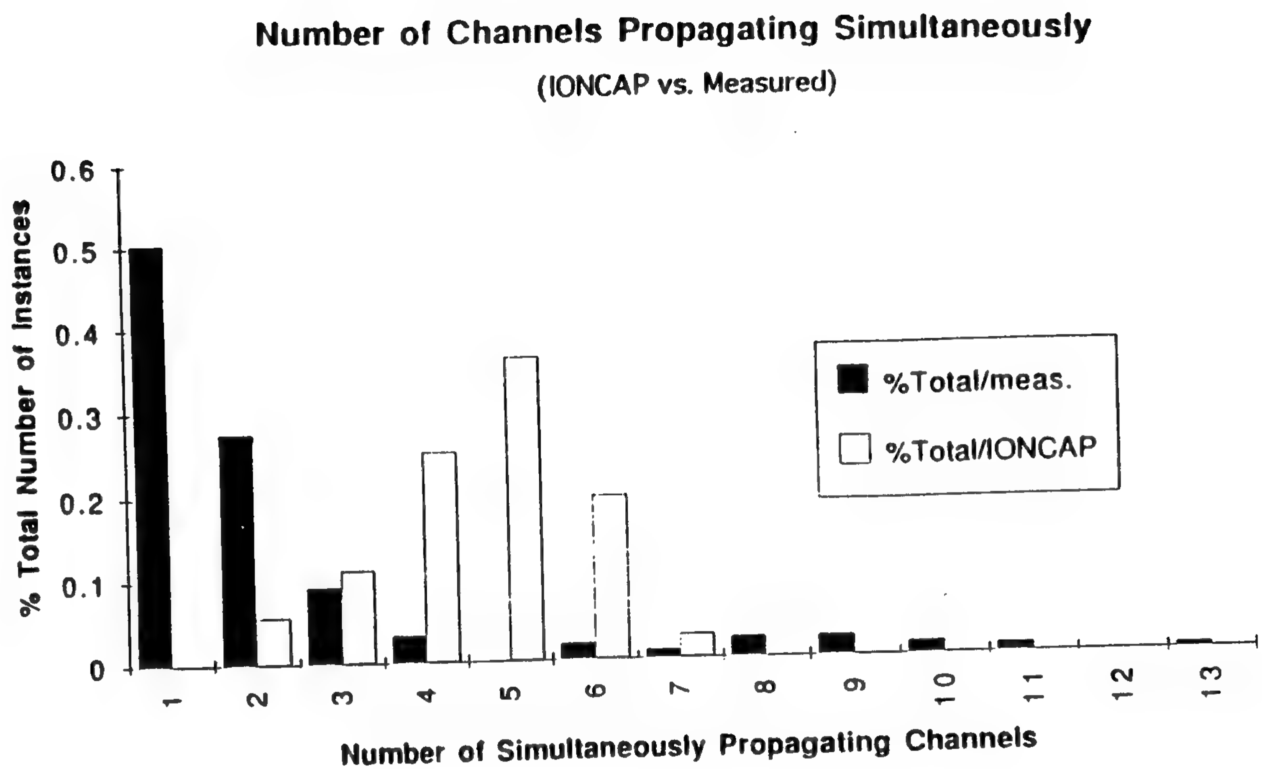

Figure 9. Simultaneously Propagating Channels, Resolute Bay to Inuvik

from six to ten simultaneous propagating frequencies. This means that IONCAP may be significantly underestimating the number of simultaneous frequencies for this link as well.

3.2.4 Channel Persistence

The final comparison of predicted and measured results for the Canadian data concerns how long good propagating frequencies can be expected to last for northern channels. This point has already been touched upon in the analytic comparison of link establishment methods contained in section 2.

Only the Resolute Bay-Cambridge Bay link has so far provided statistically significant data on channel persistence. (A small amount of data on the Resolute Bay-Inuvik link has also been collected.) For this link, persistence in the band of good propagating frequencies (3 to 10 MHz) was about 50 minutes, on average (see figure 10). This is a direct consequence of the rapidly changing structure of the ionosphere used by northern paths. (See the series of ionograms for the Greenland link in appendix A.) The hourly or two-hourly IONCAP, MINIMUF, or PROPHET predictions for this link generally indicate much longer persistence than this (five hours or more).

The short persistence of frequencies actually tried for this link (and the Greenland link discussed above) suggests that re-establishment of TADIL links will be required more frequently on northern links than on midlatitude links. This is one of the best arguments for an ALE system as an aid to communication in the north.

It is interesting to note that there is a local maximum in the curve of measured persistence versus frequency for this link at 20 MHz. This shows the persistence of frequencies that rely on "sporadic E" (frequencies that are refracted from the so-called E_S-layer). Although IONCAP, for example, can predict E-layer and E_S-layer propagation, it does not predict sporadic E for this link for January, April, or August and an average sunspot number. Provided that the sporadic-E propagation observed by Nourry and his colleagues lasts long enough to be useful for TADIL operations, frequencies that use it could be found by ALE. Since the E_S-frequencies in this case are well above the MUF, this would not happen in the conventional linking approach.

3.3 ICELAND P-3C EXPERIMENTS

These experiments, which started and ended at Keflavik, Iceland, and took place over the Norwegian Sea, involved several flights of a Navy P-3C patrol aircraft. The flights lasted three to five hours and the P-3C flew up to about 500 miles to the east of Keflavik. The flights took place between 12:00 and 02:00 GMT, which coincided with local time in Iceland. Most test data were collected during daytime hours. The data report [9] indicated that the region covered by the flight experienced historically poor HF communications.

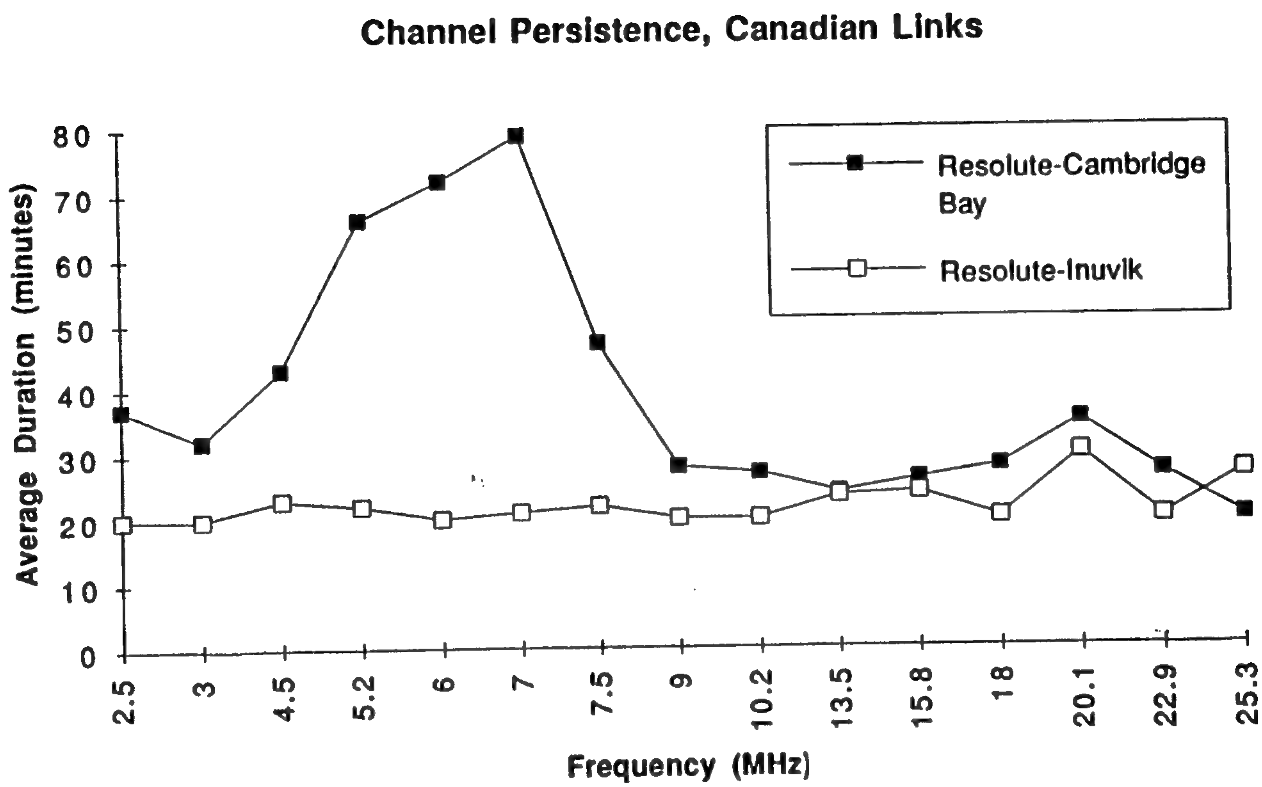

Figure 10. Channel Persistence, Resolute Bay-Cambridge Bay, Resolute Bay-Inuvik

The aircraft was equipped with a Rockwell Automatic Communications Processor (ACP) ALE device, which used a binary FSK waveform and the Rockwell Selscan™ automatic linking protocol. The waveform and associated error-correction scheme are somewhat less robust than the newer MIL-STD-188-141A waveform and error-control schemes, but the linking protocol is similar. These facts suggest that a MIL-STD-188-141A modem would have performed better than the Rockwell ACP used in these trials.

The ACP was programmed to try ten frequencies that covered the HF band from 3 to 22 MHz. During each flight out of Keflavik and back, the ten channels were evaluated twice an hour via automatic link quality analysis (LQA) soundings from Keflavik or from the P-3C. Also, twice an hour the aircraft tried an automatic call to shore, and the shore tried an automatic call to the aircraft. Manual calls on scheduled (not automatically chosen) channels were also tried twice an hour. (Although the manual calls did not follow propagation predictions, all the assigned frequencies were tried over the course of two hours of flight, so both successful manual attempts and successful automatic attempts could be compared with predictions.) Finally, slow-speed teletype messages using unprotected binary FSK were also sent twice an hour in each direction.

Although no data were collected on the conditions of the ionosphere during the tests, the comparison showed that the ACP performed much better than the manual approach. A total of 97 percent of the automatic calls (which used the twice-hourly, channel-quality updates to choose their frequencies) were successful (192 links out of 197 attempts in either direction), whereas only 61 percent of the manual calls (not, however, always tried at reasonable frequencies) were successful.

The average time to link establishment was about half a minute. (This was a function of the number of stations called (here, one) and the settings of certain timing parameters, and will be somewhat larger for the net calls that would probably be used to set up links for TADIL operations.)

Figure 11 (taken from [9]) shows the frequencies that were chosen by ALE during one of the flights versus the MUF and FOT predicted by the PROPHET program. The flight took place during the daytime. The plot is similar to those for other daytime flights near Keflavik. During most of this flight, the frequency chosen by ALE was 2 to 3 MHz above the predicted MUF. This, as with the Canadian data, is in contrast with the short Norwegian link referred to above, for which the IONCAP overestimated the MUF.

We should emphasize that most data from these experiments pertain to daytime propagation conditions. Simulations of the daytime position of the auroral oval on the dates of the Iceland flights show that the oval was above the radio paths between the P-3C and Keflavik.

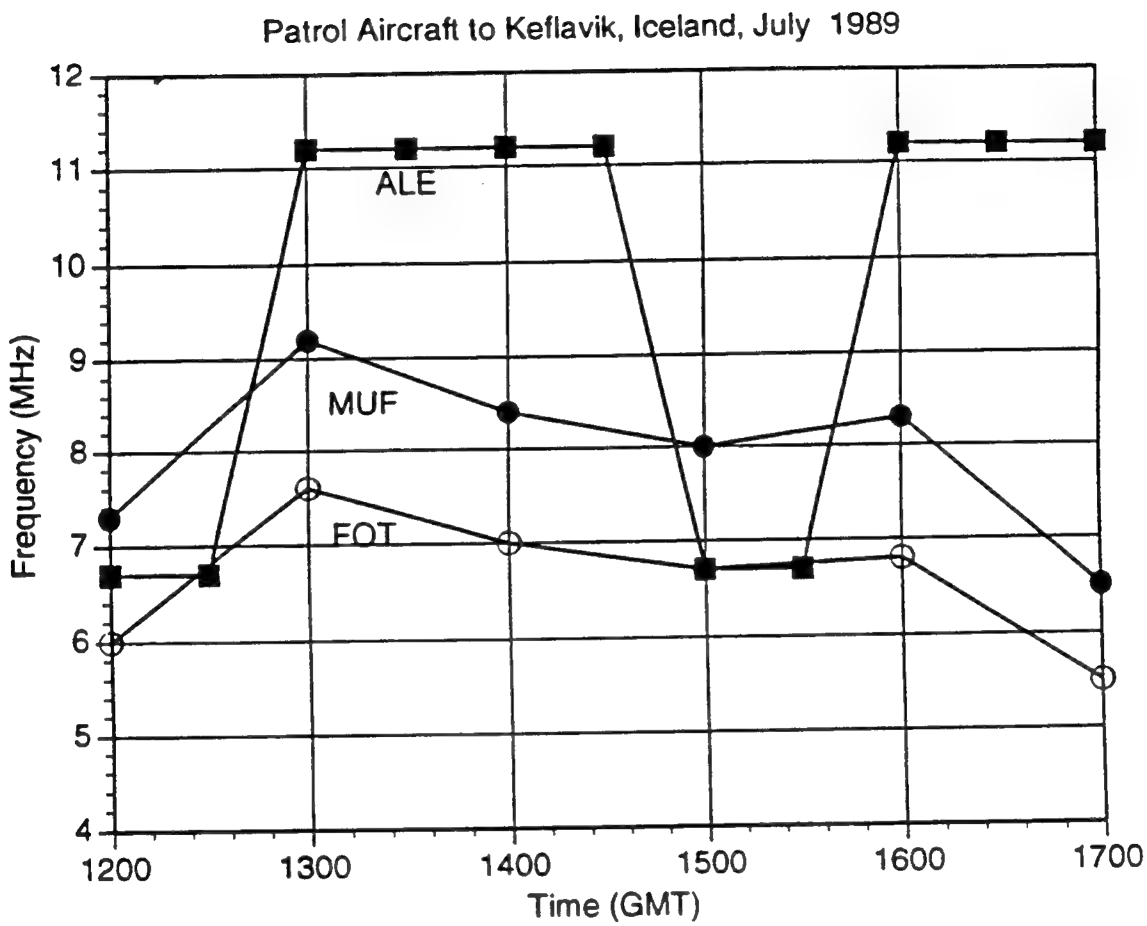

Figure 11. ALE Frequency vs. MUF and FOT for the Navy P-3C Flights

Thus, the auroral curtain can be expected to not have had much effect on HF communications during the day. On the other hand, simulations show that the most highly ionized part of the nighttime oval was near the center of the radio path, so that the auroral curtain may well have had a significant effect on HF propagation at night. The results on ALE performance reported in [9], which pertain mainly to daytime operations, should therefore be viewed as being somewhat optimistic as a guide to ALE performance during nighttime operations near Iceland.

SECTION 4

RISKS ASSOCIATED WITH DEVELOPMENT OF AN ALE-TADIL SYSTEM

In this section, we discuss the risks associated with the use of an ALE system in conjunction with TADIL A operations in the north. We discuss systems with both independent ALE and TADIL A operations (in which coordination is handled manually) and those with a system controller that automatically coordinates ALE and TADIL A operations.

4.1 MISIDENTIFICATION OF USABLE CHANNEL

Since the Military and Federal Standard ALE system uses a serial-tone waveform and error-correction coding technique (including interleaving and repetition) significantly different from those of the TADIL system (which employs a parallel-tone waveform and can use frequency diversity but no interleaving), it is possible that the ALE modem will find channels that it determines are good, but which are not usable by the TADIL modems. It is also conceivable that the reverse might happen: the ALE modem fails to make a link on a frequency the TADIL system could use. These possibilities, which would affect both independent and integrated ALE-TADIL systems, are more likely in the north than at midlatitudes, where generally less disturbed propagation conditions would keep ALE and TADIL modem performance similar.

If these phenomena happen frequently during northern operations, they may lead to situations in which ALE finds "good" channels in response to a TADIL link failure that TADIL cannot use. Alternatively, ALE might fail to find channels that TADIL can use.

Since the ALE waveform and error-control schemes were designed to cope with widely varying channel conditions, including both uniformly distributed ("random") and bursty bit errors, it is likely that ALE performance will be better than TADIL performance in the fast-fading and severe delay-spread conditions typical of disturbed northern operations. This suggests that the ALE modem would more often suggest channels that TADIL could not use, rather than vice versa. The channel ranking produced by the ALE system would nevertheless provide more accurate and more up-to-date information on channel quality than the current system (updates every half hour or so versus at most once a day). The best way to determine how often ALE performance fails to reflect TADIL performance is through on-the-air testing of both systems.

4.2 TRANSMISSION CONTENTION

This could only occur if ALE and TADIL operations were carried out on the same channels and no time-sharing scheme were used. To prevent this in the absence of scheduling, a

listen-before-transmit scheme could be employed with one or both systems. This would normally require both hardware (to detect and report on detected transmissions) and system-controller software (to prevent contending transmissions). The easiest way to avoid this risk is to carry out ALE operations on channels close to, but not the same as, TADIL channels; but this does not represent efficient (or perhaps even allowable) use of assigned frequency assets.

The most practical approach to avoiding ALE-TADIL contention is to employ a coordinated schedule of ALE LQA soundings on all the assigned channels (or some subset of them that corresponds to the time-of-day of operations) except the one currently used for TADIL. To prevent reliability problems at sites where transmitters and receivers may not be separated and in AWACS aircraft (see the following paragraphs), receiver scanning should be controlled by a system controller on each platform that allows scanning only during the period when each receiver is scheduled to receive LQA soundings from the NCS.

4.3 ELECTROMAGNETIC COMPATIBILITY ON PLATFORMS WITH COLLOCATED RECEIVERS

In this report, we deal directly with only the question of whether or not ALE (in the form of already acquired equipment at the two Canadian ground stations or contemplated additional equipment at the six U.S. stations) should be used in conjunction with TADIL A communications. Nevertheless, it is important to anticipate any risks that might arise in connection with the corresponding AWACS communications, since recommended use of ALE at the ground stations would naturally require that the aircraft ultimately also acquire ALE.

The main risk associated with airborne operations of an ALE-TADIL combination is electromagnetic incompatibility and the possibly unacceptable reliability of relay-switched preselectors that can be used to avoid it. These risks would also be run at any ground station where collocated operation of ALE and TADIL transceivers is required or contemplated.

In a location where ALE and TADIL receivers and transmitters both operate at the same time (the ALE receiver scanning or collecting LQA information, and the TADIL receiver taking part in TADIL operations), each receiver will normally require a preselector to filter out unwanted signal components from the other transmitter when the latter is operating. In the case of TADIL reception, the preselector will not normally have to switch passbands very often. In the case of ALE reception during scanning or LQA exchange, the preselector will have to keep up with the receiver's channel-switching rate, which currently is two channels per second for scanning under the ALE standards. The channel-switching rate during an LQA exchange is about one switch every few seconds.

A preselector that allows simultaneous operation of collocated ALE receivers and TADIL transmitters must have a mean time between failures (MTBF) of several thousand hours to prevent unacceptably frequent repair and system failure. Diode-switched preselectors generally are preferred to mechanically (relay) switched ones for this reason.

The ALE receivers at collocated radio sites will not have to scan during the entire time they are not involved in LQA or linking activities. They need only scan for a few minutes every hour (for example), during a brief period when the NCS is updating its channel-quality assessment. This restriction of scanning will decrease the number of times per hour the preselector will have to switch and raise its MTBF. One function of the system controller described in appendix B is to schedule and command the scanning required for regular channel-quality assessment.

4.4 ANTENNA COUPLERS ON AIRCRAFT

Since the AWACS aircraft in a TADIL net with ALE will have to respond to at least LQA or net calls (even if they don't initiate any), and since they are not generally equipped with broadband (not tuned) antennas, they will require automatic antenna couplers. These couplers will have to switch inductor or capacitor settings every few seconds during an ALE exchange; therefore, their long-term reliability will have to be high. Diode-switched (rather than relay-switched) couplers with high MTBF will be required for aircraft and for any ground stations that do not use broadband antennas.

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

We studied the improvements that ALE can offer to TADIL A data communications. We concentrated on communications in northern regions, where propagation conditions are frequently disturbed, and emphasized the length of time a channel remains useful for TADIL data transmission, which is shorter, on average, than the duration of useful transmissions at midlatitudes.

A review of the available data on narrowband and wideband communications performance in Iceland, Canada, and Norway shows that useful channels in the extreme north sometimes persist, on average, for between half an hour and two hours, whereas midlatitude channels typically persist for five or six hours outside the dawn transition period. Therefore, TADIL operations in such conditions may require relatively frequent changes of frequency as one channel fails and some other one possibly becomes useful. An ALE system can automatically assess the quality of all assigned channels (except possibly the one being used for TADIL A communications) on a regular basis before it becomes necessary to switch to one. Thus, an ALE system is the ideal way to relieve the TADIL system of the requirement that new channels be determined manually (by means of a voice orderwire) from a small number of channels suggested by the frequency coordinator before each flight.

If the ALE sounding rate is roughly equal to the rate at which channels fail and are replaced by other usable channels, then the mission availability will be raised to whatever level is supportable by the state of the ionosphere in the operating region. Determining if the resulting mission availability will exceed the desired 90-percent level will require data from on-the-air tests of an ALE-TADIL A combination in northern operational regions. Data from current Canadian tests of ALE shed some light on this question, but those tests have not provided data on the ALE-TADIL A combination.

We recommend that further data on ALE-assisted TADIL communications be collected using the already acquired equipment. Initially, such data collection can be from operations between ground stations, as in the Canadian tests, but ultimately, tests in northern regions between ground stations and ALE-equipped aircraft should be carried out. RADIL should consider setting up and gathering additional propagation data from ALE-equipped ground stations in the north even before AWACS aircraft are equipped with the ALE capability. Some of the data such stations can provide could be collected at ALE-equipped sites that already exist, such as those at MITRE's sites in Bedford, MA, and McLean, VA. Setting up and operating an ALE-equipped ground station is inexpensive compared with the cost of equipping an aircraft with ALE. The station could be used later for frequency management and propagation prediction in support of ALE-assisted flight communications.

The most efficient operation of a network of ALE-assisted TADIL stations is facilitated by a system controller at each station that automatically coordinates the operation of the ALE modem and its transceiver with that of the TADIL A modem and its transmitter and receiver (or transceiver). We recommend that the development of such a controller (which might become part of the current TADIL A controller) be investigated. In the absence of a system controller, coordination of the ALE and TADIL systems must be performed by an operator at each radio station. This is still an improvement over the current approach.

The MITRE Corporation's tasking that led to this report did not call for investigating the performance of the TADIL A system itself. However, the relatively non-robust nature of the TADIL A waveform and error-correction scheme [10] suggests that there may be times when an ALE modem with its robust waveform and error-correction scheme will establish a link on a channel that the TADIL modem cannot use, or can use for only an unacceptably short time.

It is important to gain an understanding of how well the TADIL A system itself might perform (especially in northern channels) if it is upgraded by the addition of ALE. Such an understanding can be gained best with on-the-air tests. If tests show that the TADIL A waveform is not as robust as the ALE waveform in northern regions, it is possible that a more robust waveform and signal processing will do better than TADIL A there. Such waveforms might then be considered for northern operations. Some examples of such waveforms are the serial-tone, PSK-modulated waveform prescribed by MIL-STD-188-110A [3], which is implemented in NDI modems, and a wideband (1-MHz bandwidth) waveform developed by The MITRE Corporation. We recommend further analytical and on-the-air comparison of the performance of TADIL A and more robust waveforms operating in northern conditions.

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APPENDIX A

IONOGRAMS FROM BENIGN AND DISTURBED CHANNELS

This appendix shows two series of ionograms from actual links. One series is for a benign link and one is for a disturbed northern link. Both links have about the same length and orientation.

Figures A-1a through A-1e (see end of appendix) show a series of five ionograms (taken on 30 March 1992) for the 1600 km east-west high frequency (HF) path between Scott Air Force Base in west-central Illinois and Bedford, MA, near Boston. The ionograms were taken every 15 minutes and cover about an hour-and-a-half starting at 21:49 Greenwich mean time (GMT) (about 16:00 at the path midpoint). They have the general "benign" appearance of most other ionograms that might be taken during the daytime on this link. There is a clearly defined and stable range of frequencies below the maximum usable frequency (MUF) where there are neither E-layer returns nor 2F returns. In the absence of strong interference from signals outside the net, Tactical Digital Information Link (TADIL) A communications could be carried out on frequencies in this range for several hours before a change of frequency (in this case only to track a fall in the MUF as the ionization of the ionosphere decreased with advancing night) would be necessary.

Figures A-2a through A-2f (immediately following A-1e) show a one-and-a-half-hour series of six (narrowband) ionograms taken for the Greenland link referred to above. The series starts at 18:50 GMT and corresponds to the same local time at the path midpoint (about 16:00) as the ionogram series taken for the benign link discussed in paragraph 2.2. This link has about the same orientation and length (1400 km) as the benign link. The differences between this series and the benign one are striking. Although the two series show roughly the same MUFs (between 15 and 17 MHz when the MUF can be ascertained in the Greenland series), the Greenland series is uniformly more diffuse than the benign series. The curved 1F trace is filled with returns that suggest there is no sharply defined edge of the F-layer for this link: radio signals will be "smeared" in terms of arrival time at a receiver, which will cause inter-symbol interference at the demodulator input and high bit-error rates for TADIL communications.

With the exception of the last ionogram of the series (figure A-2f), which marks the start of a half-hour return to slightly better propagation conditions, the 2F signal returns are also diffuse, and it is often difficult to separate them from 1F returns. This would also lead to complicated smearing of received TADIL signals. In the third and fourth ionograms are "plumes" that extend upward and to the right of the fold-back at the MUF. These are probably "slant-F" formations connected with "tilts" in the F-layer. The tilts are generally caused by the near-vertical alignment of the magnetic field lines in the far north.

Non-horizontal alignments can lead to inhomogeneities in the ionospheric ionization density whose sizes are commensurate with the wavelength at several frequencies above the MUF. These moving, wavelength-sized inhomogeneities may be the source of the plumes in these ionograms. Transient slant-F returns can cause severe delay distortion of narrowband signals, along with unpredictable and generally short-lived opportunities for communications at frequencies above the MUF.

The E-layer is also diffuse in the ionograms, and the set of frequencies at which it is present changes rapidly. This suggests that the E-layer would have an unpredictable and—because of the rapidity of the changes—probably deleterious effect on TADIL communications over this link under the conditions illustrated in the ionograms. This series is typical of other ionograms taken for this link during these experiments, and it gives an idea of the differences between propagation in the north and at midlatitudes.

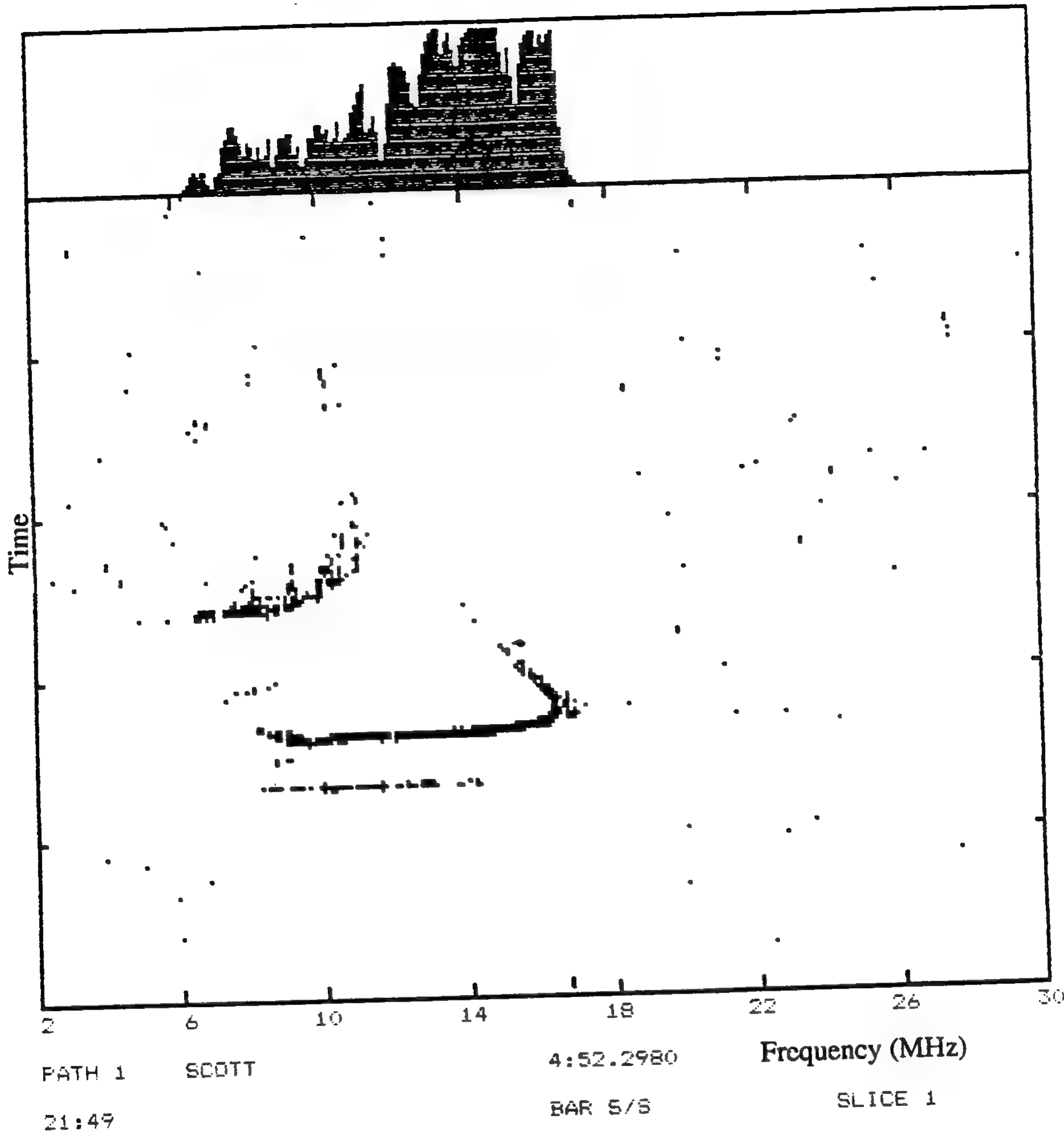

Figure A-1a. Scott AFB-to-Bedford, 21:49 GMT

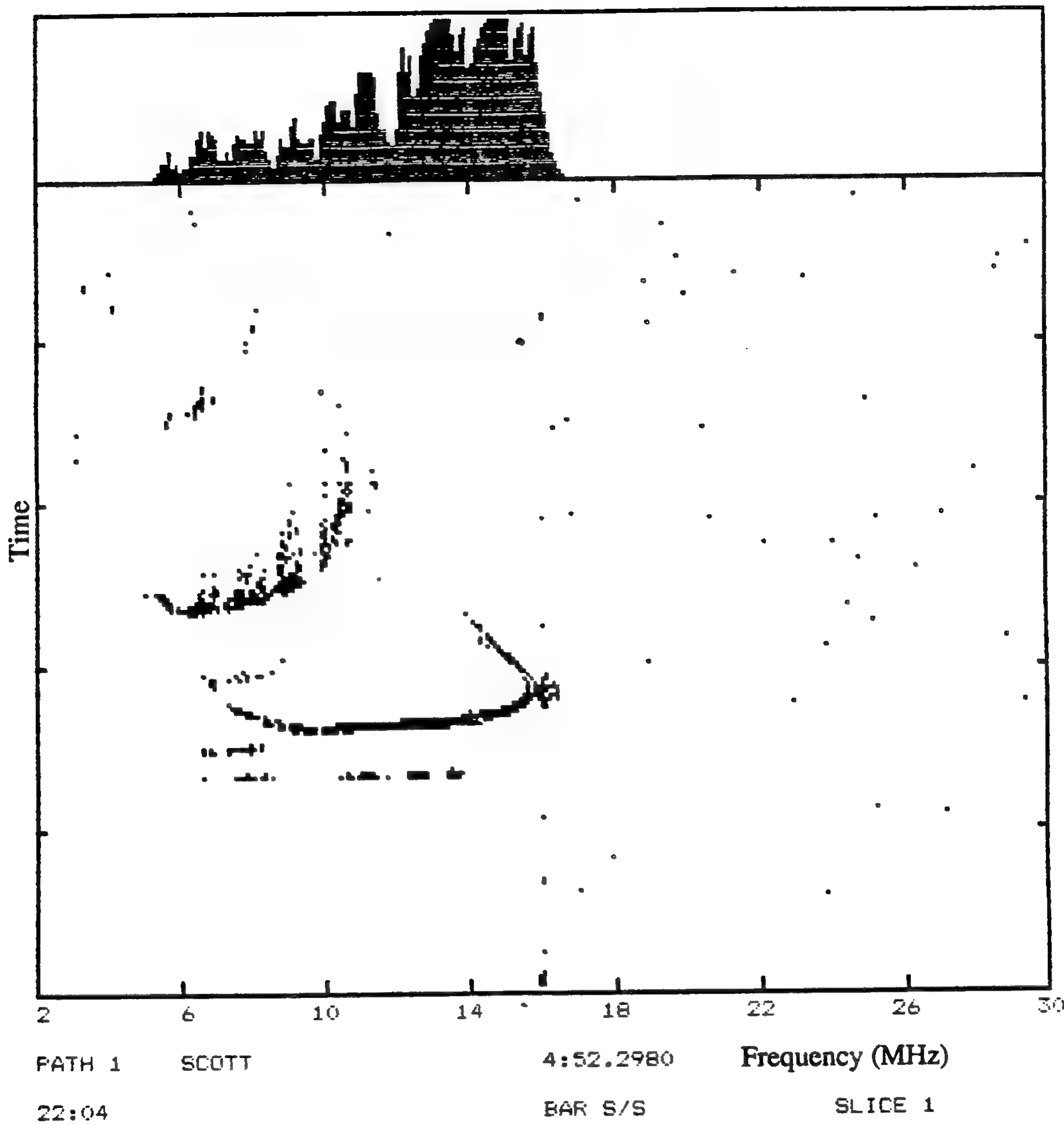

Figure A-1b. Scott AFB-to-Bedford, 22:04 GMT

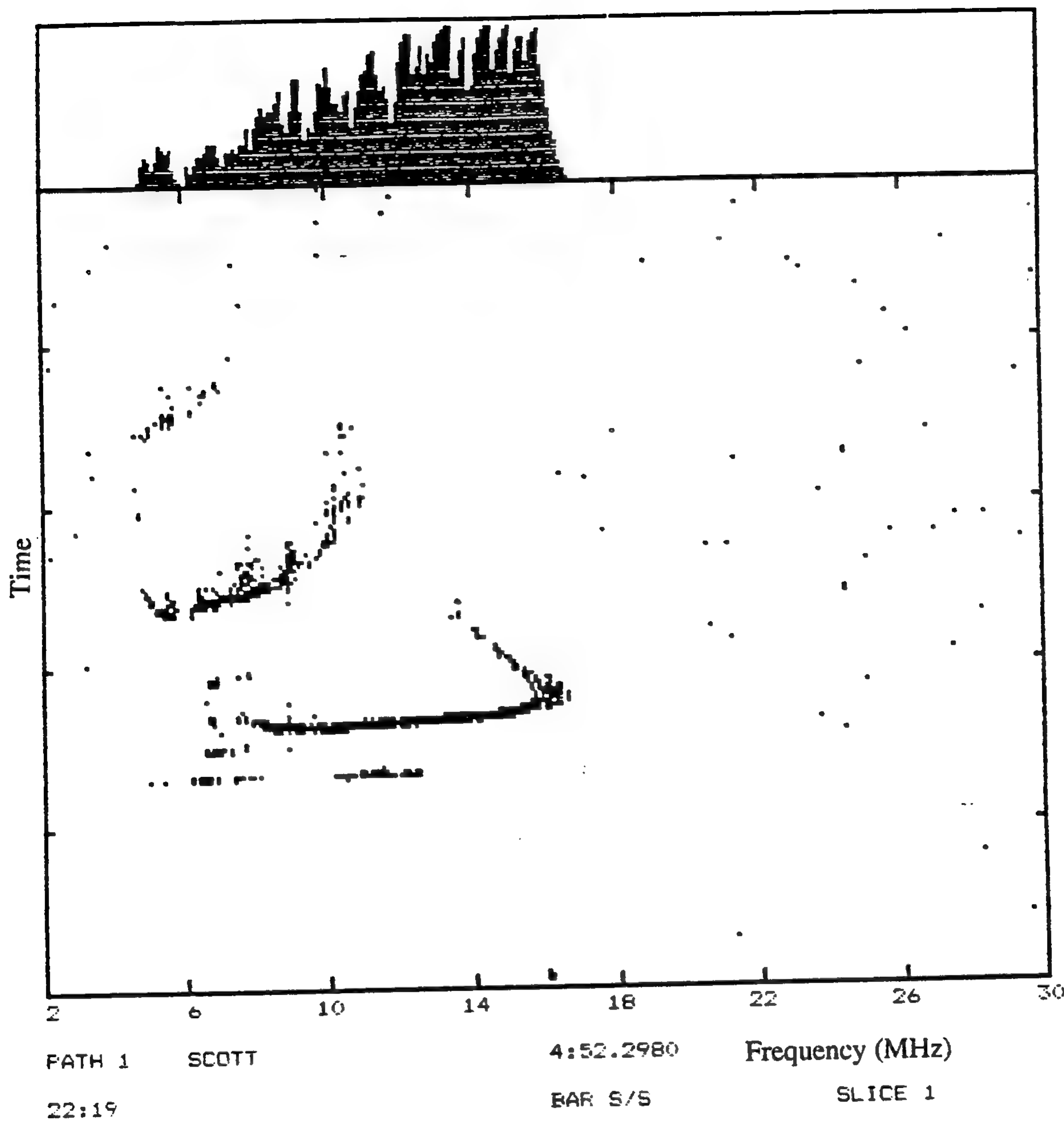

Figure A-1c. Scott AFB-to-Bedford, 22:19 GMT

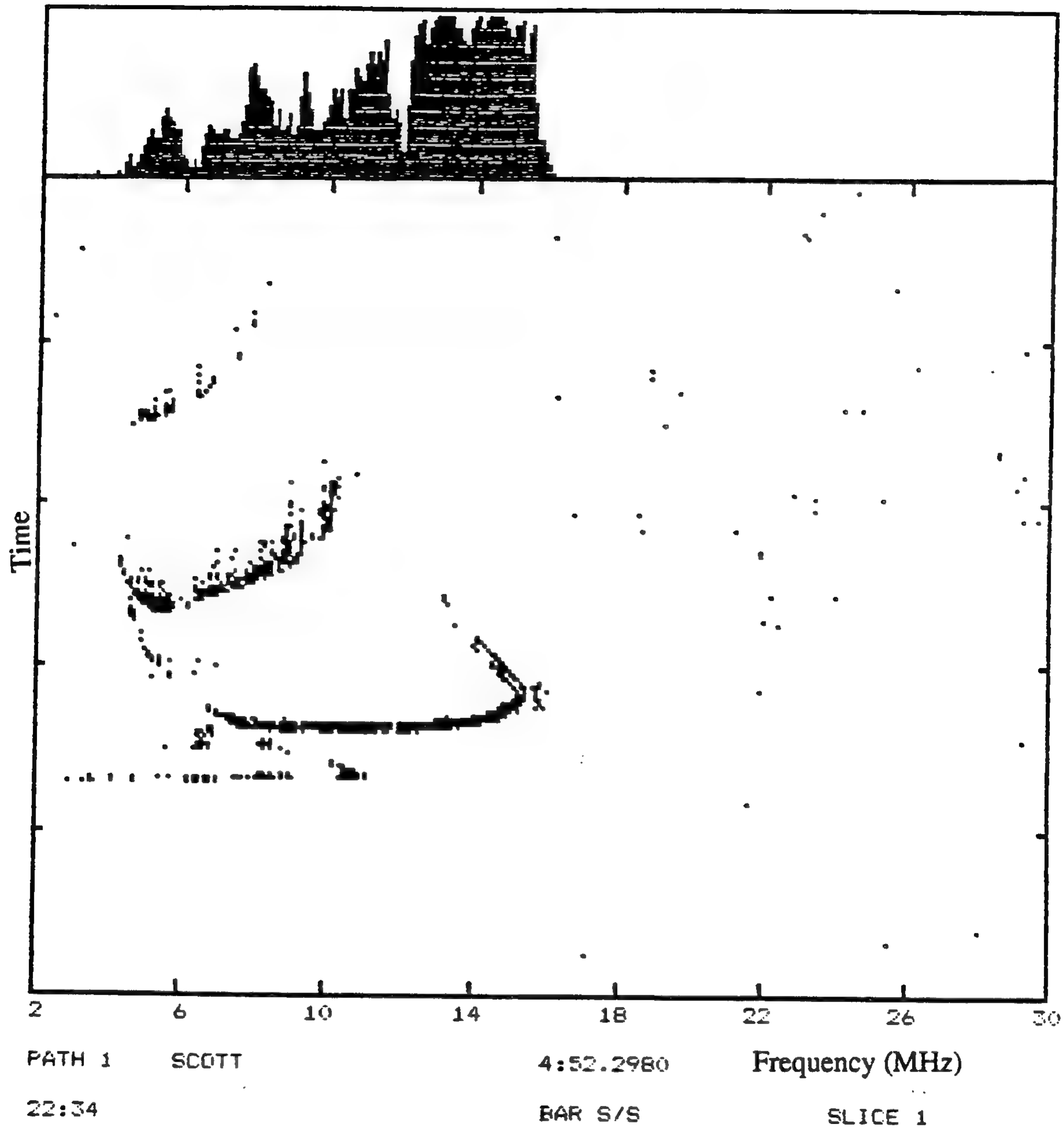

Figure A-1d. Scott AFB-to-Bedford, 22:34 GMT

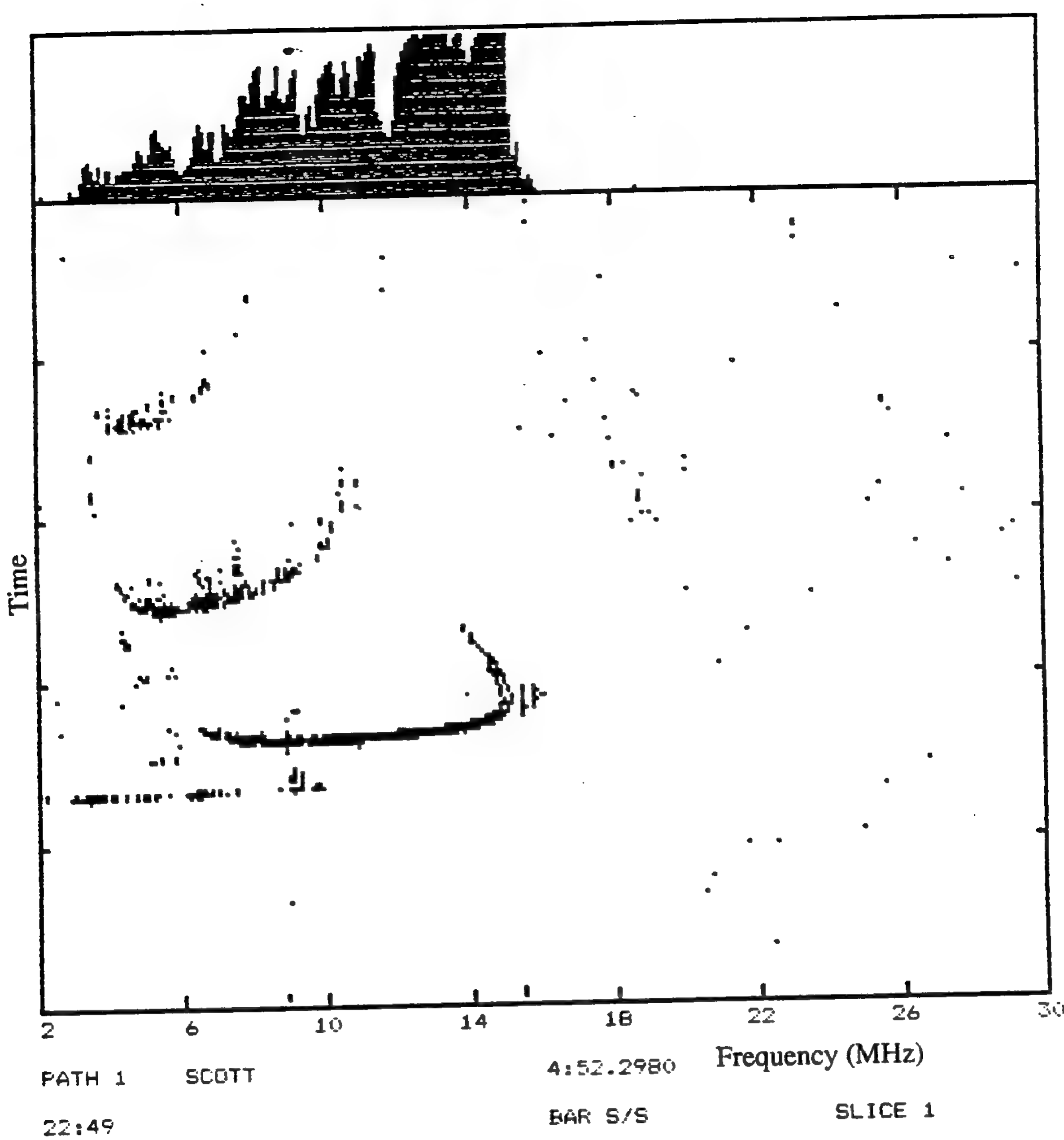

Figure A-1e. Scott AFB-to-Bedford, 22:49 GMT

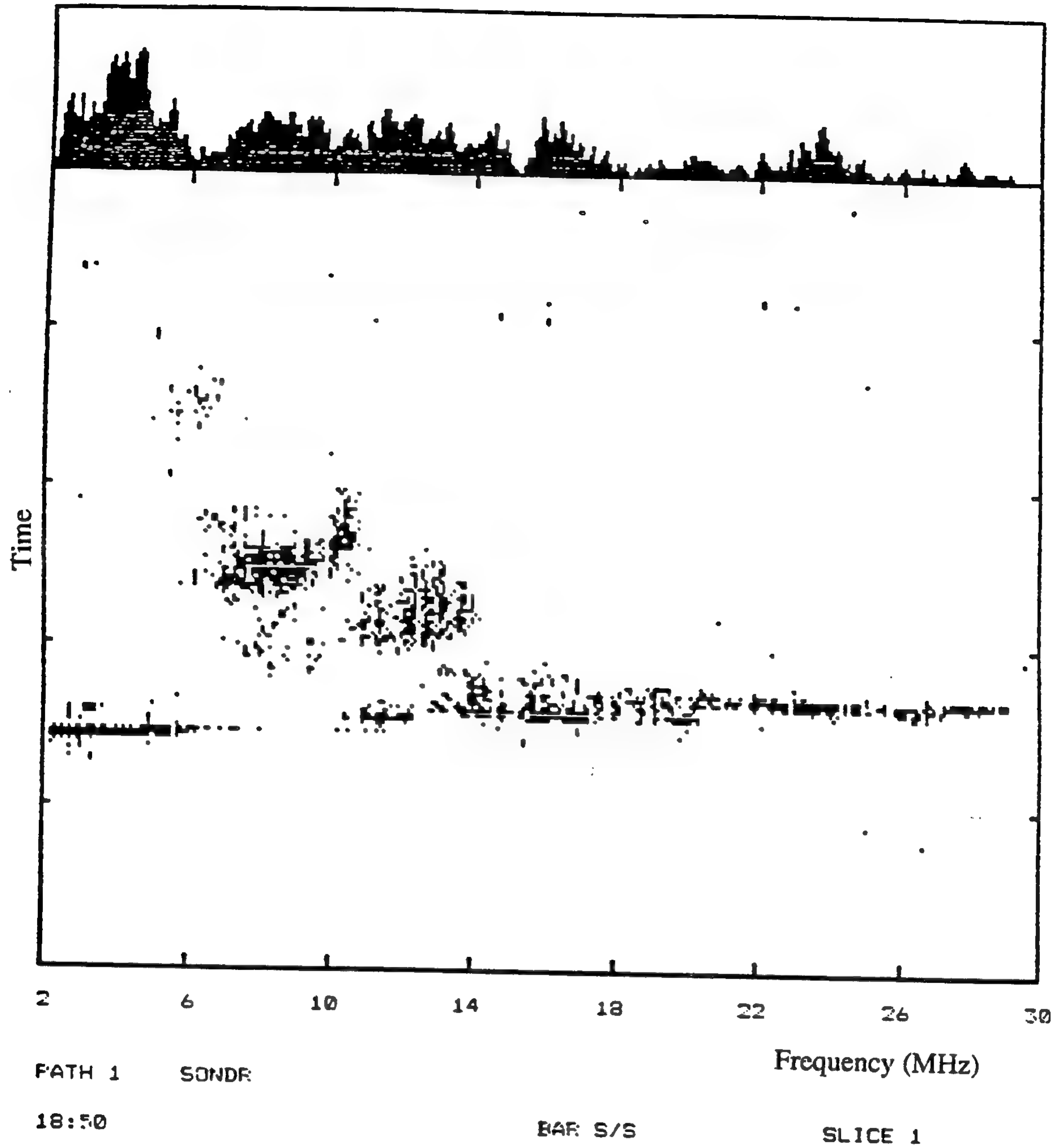

Figure A-2a. Sondrestrom-to-Keflavik, 18:50 GMT

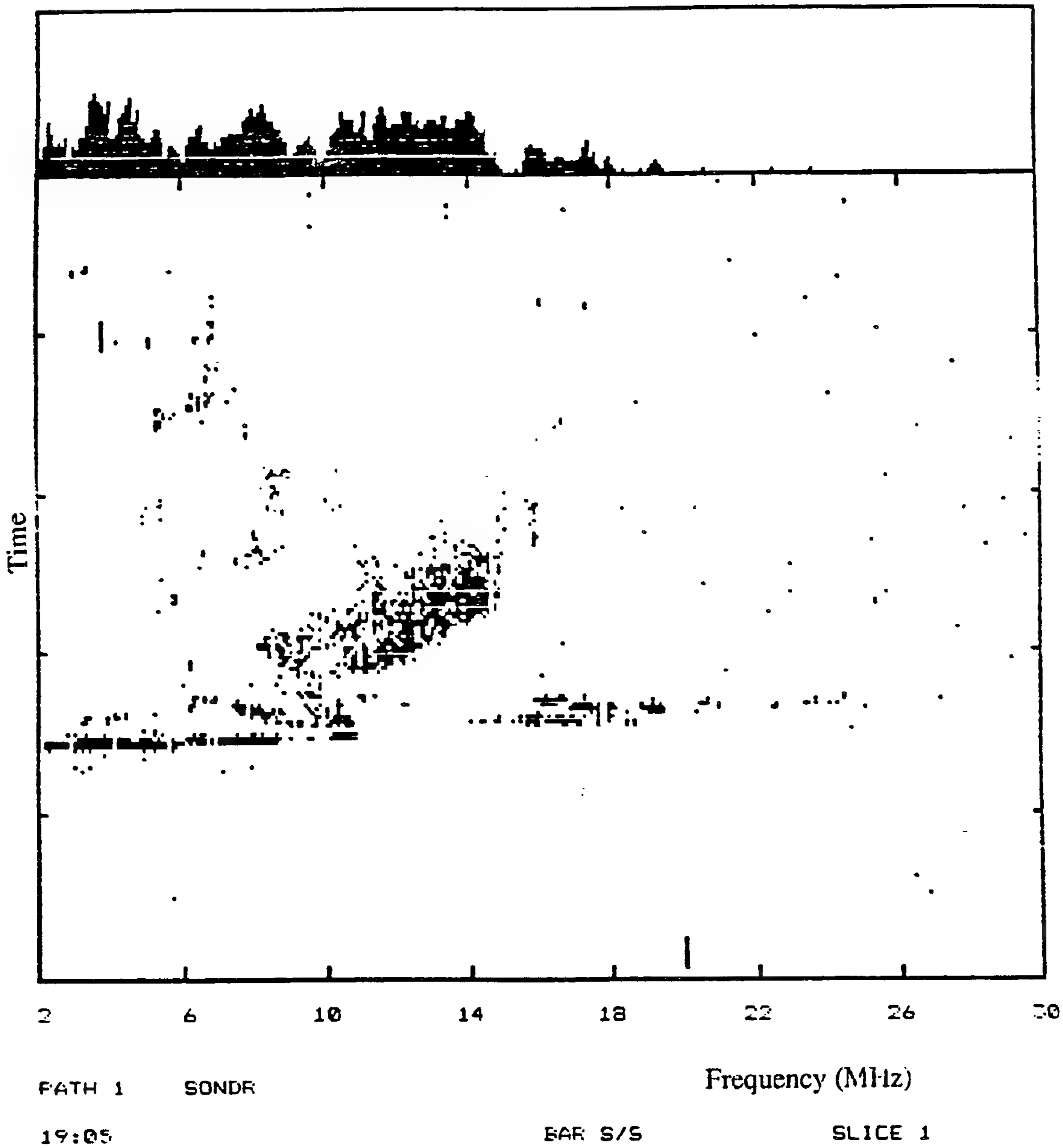

Figure A-2b. Sondrestrom-to-Keflavik, 19:05 GMT

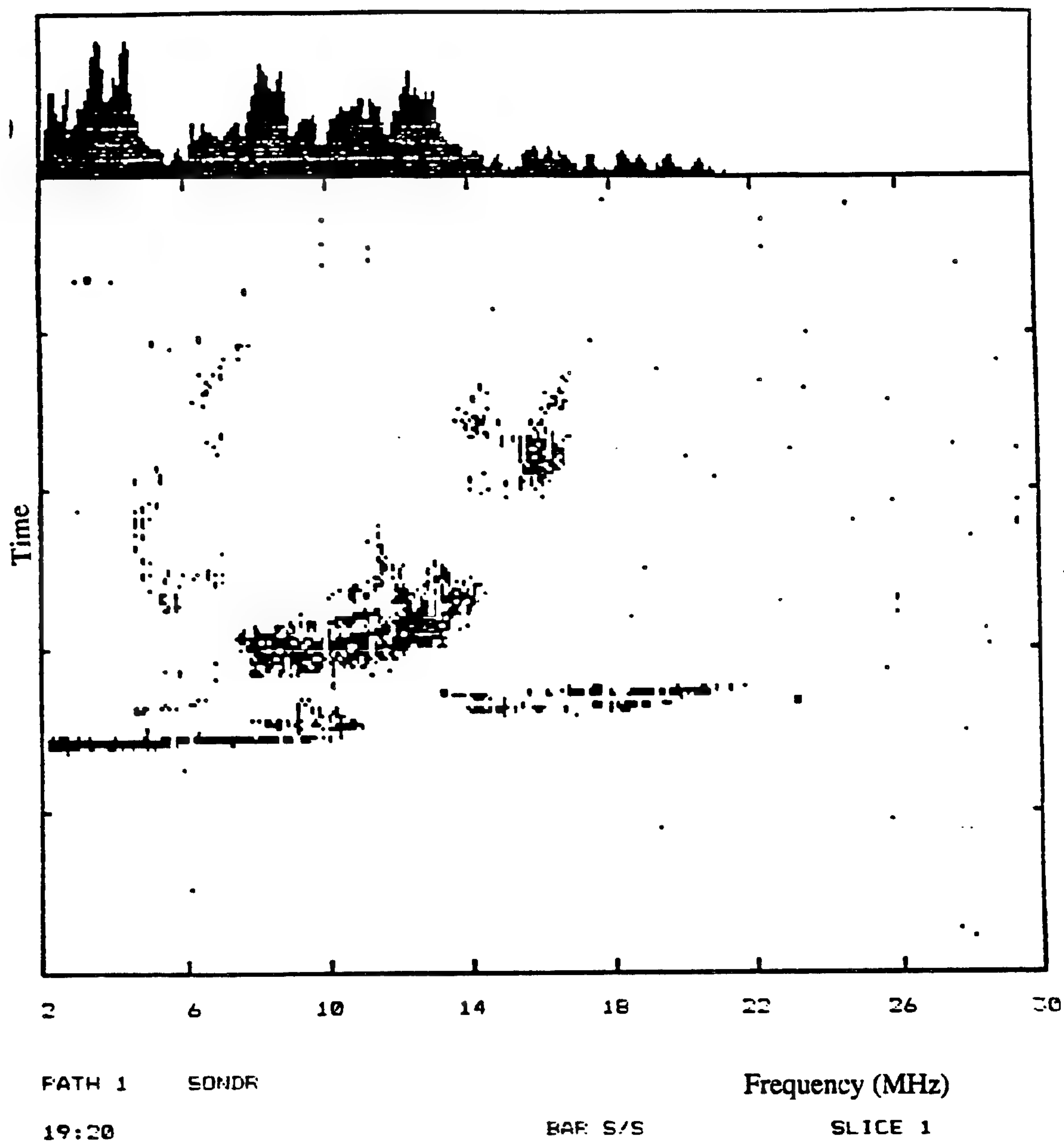

Figure A-2c. Sondrestrom-to-Keflavik, 19:20 GMT

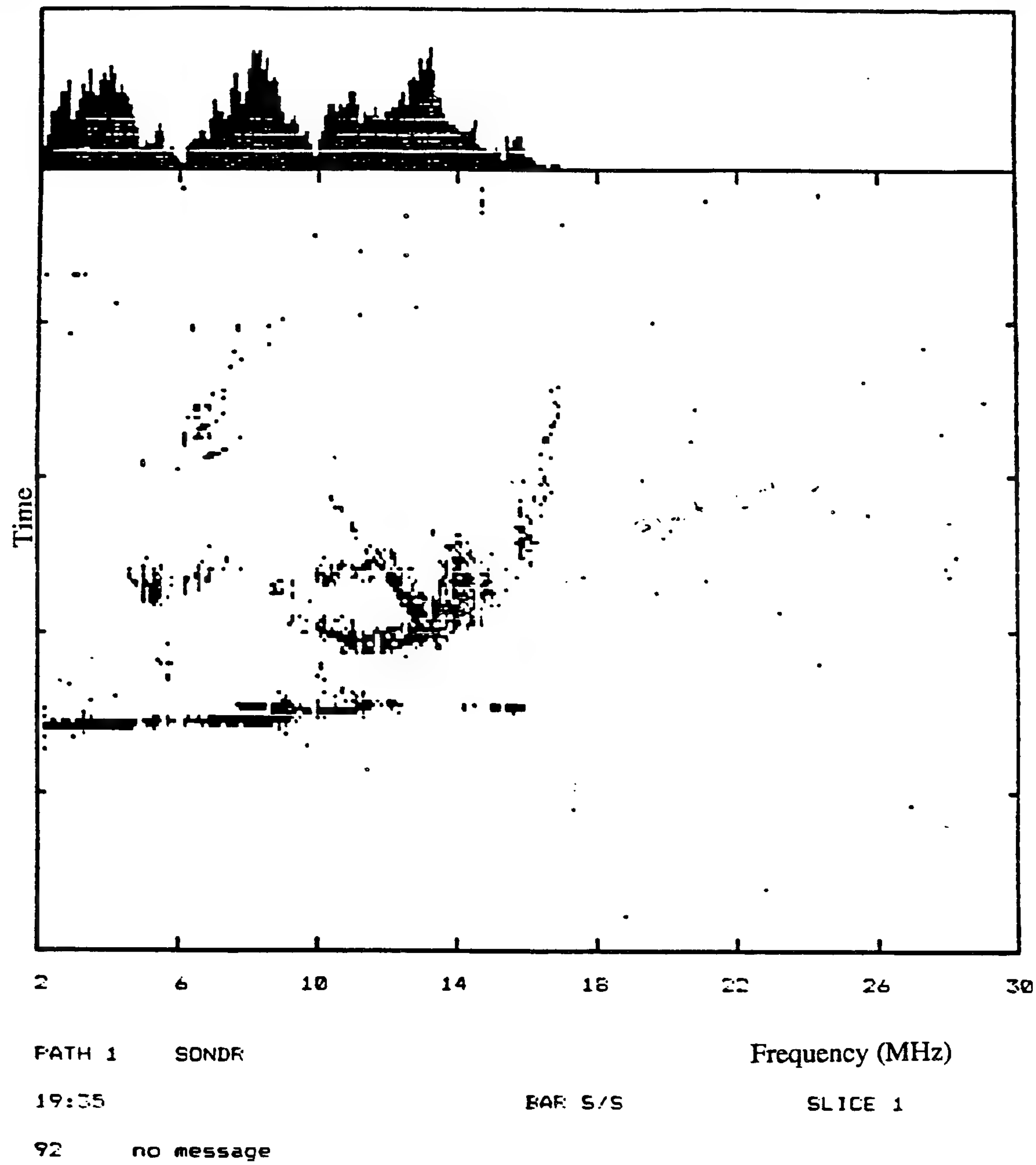

Figure A-2d. Sondrestrom-to-Keflavik, 19:35 GMT

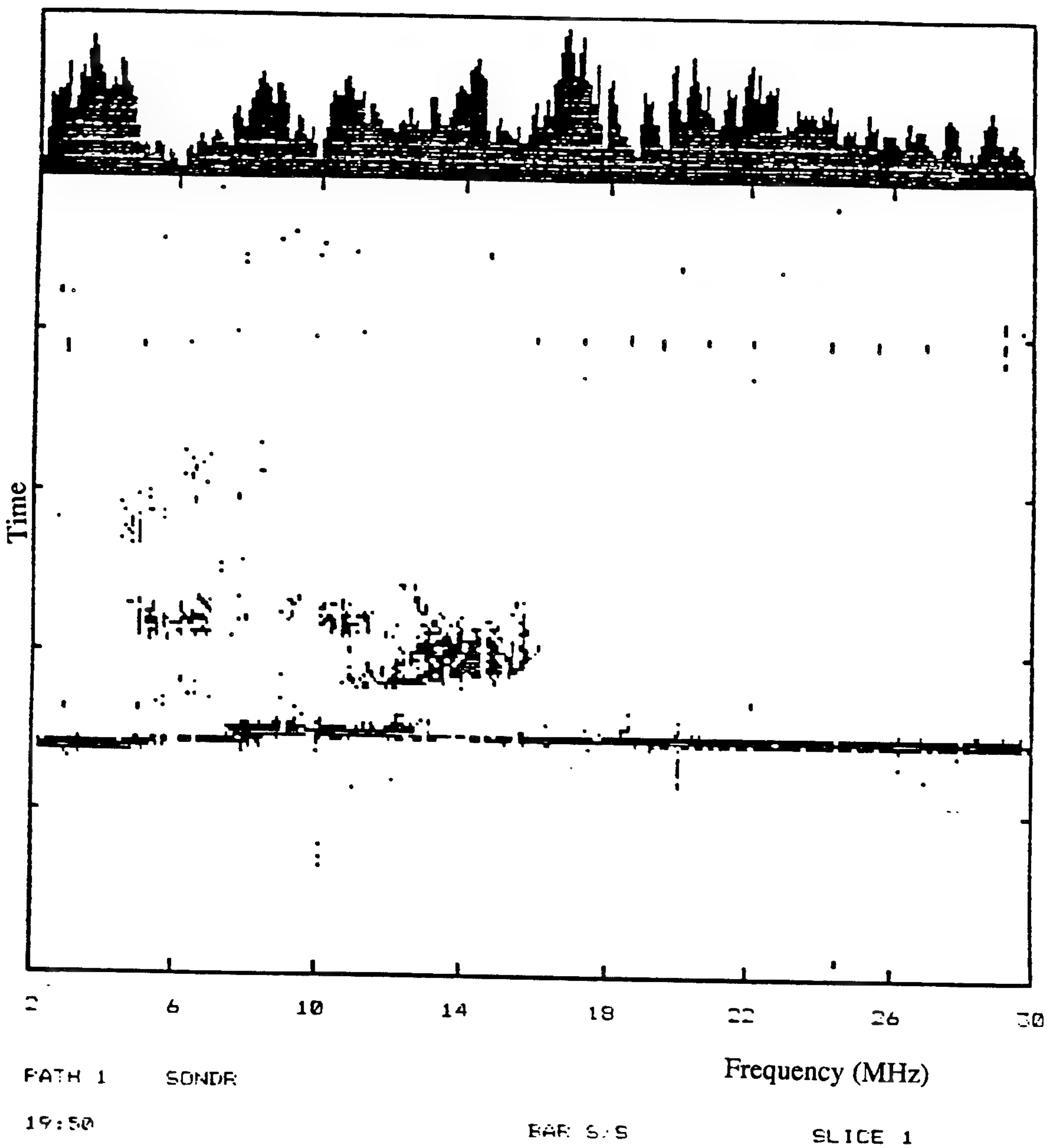

Figure A-2e. Sondrestrom-to-Keflavik, 19:50 GMT

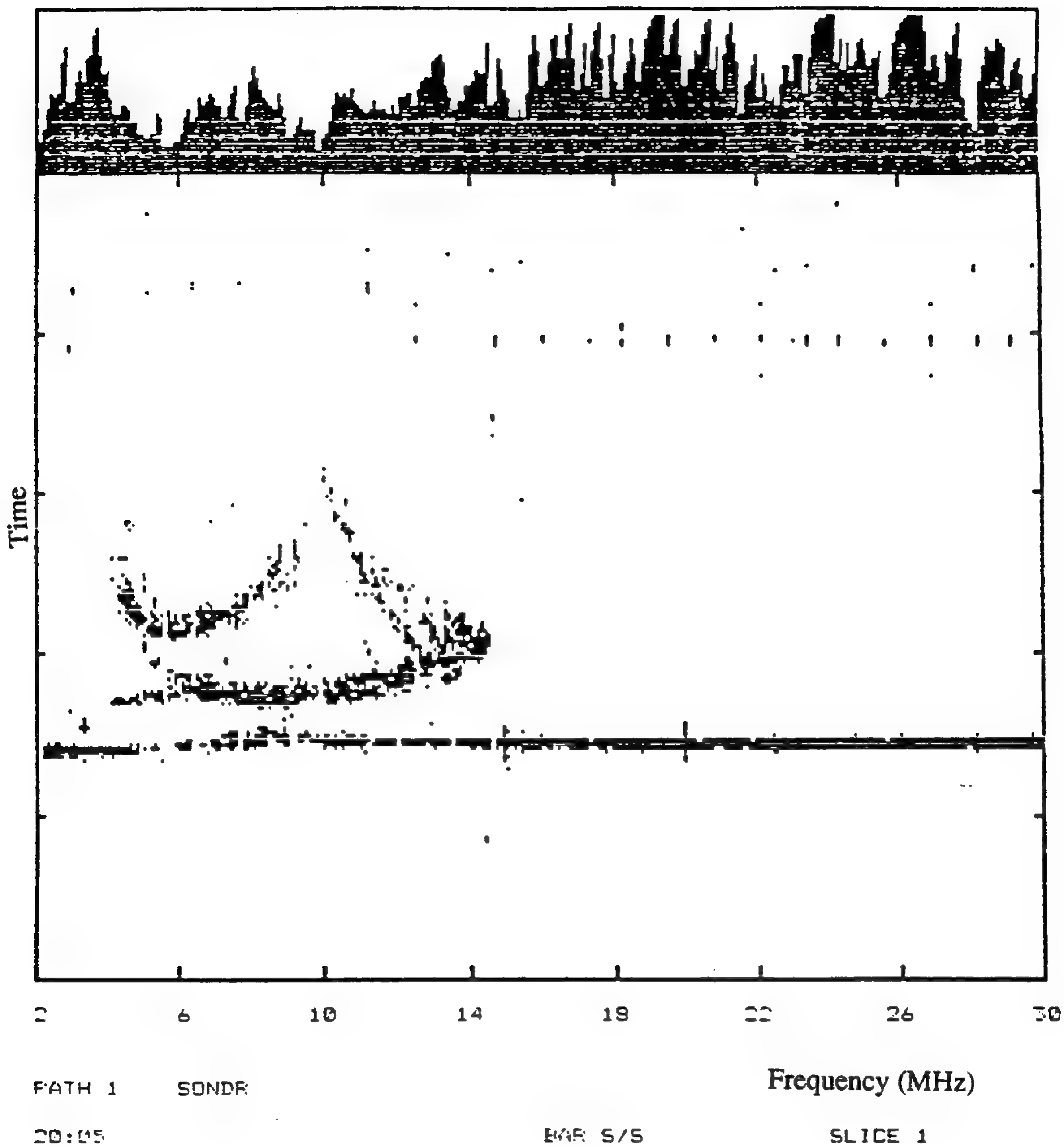

Figure A-2f. Sondrestrom-to-Keflavik, 20:05 GMT

APPENDIX B

SYSTEM CONTROLLER DESCRIPTION

The system controller is a dedicated processor connected via control and data bus interfaces to high frequency (HF) radios at Tactical Digital information Link (TADIL) A ground stations and possibly also in Airborne Warning and Control System (AWACS) aircraft. Figure B-1 shows the general layout of a Regional Operations Control Center AWACS Digital Information Link (RADIL) node equipped with such a controller. The main purpose of the controller is to automate control of automatic link establishment (ALE) operations, or ALE and TADIL A operations, so as to minimize operator intervention when HF radio system operational parameters need to be changed in response to mission requirements, and generally to increase the efficiency of TADIL data communications. The size and exact properties of the system controllers, modems, and radios at ground stations and AWACS aircraft may be different.

The basic ALE radio controller (which is a part of an ALE radio system on ground or airborne platforms) provides only the link level functions defined in MIL-STD-188-141A. To carry out the complete AWACS TADIL A communications mission, several network and higher level radio control functions must be provided by the operator or a "system controller." Without an additional system controller, these higher level functions are operator-intensive and may require more than one person to carry them out. The desirability of a system controller will become apparent from the system control requirements described below.

B.1 ALE CONTROL

The system controller must be capable of initialization and command of the ALE radio controller at its site so that a pre-programmed network configuration can be loaded into the ALE modem, and operational sequences can be executed automatically through a single command or a series of commands from the operator. This control includes loading scan lists and network configuration and all the necessary ALE and link quality analysis (LQA) functions, such as sounding, LQA data exchanges, scanning, and calling.

The scan lists should be changeable during network operation so as to accommodate changing mission needs.

Since the most efficient use of assigned frequencies is for scheduled LQA calls to take place on frequencies not being used for TADIL communications, the system controller should also be capable of automatically scheduling receiver scan cycles at the ground stations (and preferably also in aircraft). This would have to be performed manually in current systems.

B.2 ALE DATAFILL

The automatic loading and configuration of ALE controllers described above is normally implemented using "datafill files." A datafill file is a series of ASCII text lines that meet specific form and content rules that allow the required operating parameters to be read into the ALE controller quickly and accurately. The datafill files are stored on floppy disks or similar transportable media for distribution to the net members on a regular schedule, say before each flight, or weekly, or monthly. Modern ALE controllers usually come with a means for automatic datafill, although their datafill format may have to be tailored to AWACS TADIL A requirements.

B.3 MARGINAL LINK ALARM

The system controller working in conjunction with the ALE controller should provide selectable visual and audible alarms that alert the operator to an impending link failure, so that appropriate corrective action can be taken. The threshold for such an alarm is determined from the available LQA data and its associated confidence factor.

B.4 DIURNAL FREQUENCY MANAGEMENT

The system controller must be capable of storing (in random access memory (RAM) and on a transportable medium) scan and network configuration lists based on time-of-day, predicted optimal working frequency (FOT), and stored LQA data (when available). This capability is required to provide pseudo-real-time updates to the ALE controller's database when LQA exchanges are not possible, such as during unexpected mission changes or unexpected changes in network configuration, caused, for example, by equipment failure at one or more TADIL A network nodes.

B.5 CONTENTION CONTROL

In the absence of operational procedures that avoid contention between prospective users of the same channel, the system controller should be capable of following listen-before-call (LBC) and listen-before-data-transmission (LBDT) protocols. The system controller-plus-radio system (or, in its absence, the operator-plus-radio system) must be capable of recognizing channels occupied by ALE, SSB voice, and TADIL A modem data signals, and taking appropriate action to prevent contention if the operational procedures (such as use of ALE and TADIL A on the same channels) might otherwise allow it.

The contention control procedures must be tailored to match the mission requirements for priority and throughput in specific modes of operation. For example, the inhibiting of particular automatic ALE functions, such as alternate channel selection after LBC or LBDT

indicate busy channels, and automatic response to certain calls may be necessary in certain operating scenarios. The parameters that set the contention control protocol should be programmable through datafill entry or by the operator.

B.6 ALE AND TADIL A MODEM COORDINATION

There are two basic ways in which a system controller can be used during operation of an ALE-assisted TADIL A network. The simpler approach is for the controller to control the ALE modem alone, either on separate (nearby) channels, or on TADIL A channels when the TADIL A modems are not in use. In this case, the system controller would be used for datafill, LQA-scheduling, and (orderwire) call-scheduling, and the operator would use information provided by the ALE system to coordinate TADIL A communications.

The preferred approach is to use the system controller to control both the ALE system and the TADIL A system. In this approach, the controller would carry out the datafill, LQA- and call-scheduling functions, and coordinate use of ALE information by the TADIL A system to change channels when the current one fails or begins to fail. In the ultimate version of such an approach, the system controller would integrate its functions with those of the present TADIL A Data Terminal Set. It would automatically gather ALE information and use it to operate the TADIL system. In this approach, the system controllers on aircraft would probably play a role subordinate to the role played by the system controller at a ground station, which would normally be the NCS.

In both approaches, ALE net calls would be carried out by the system controller on a regular schedule (determined by the channel conditions and mission requirements) to determine which frequencies were suitable for TADIL A network communications should a network frequency change become necessary.

One should bear in mind that developing a system controller to control and coordinate both ALE and TADIL systems, although desirable from an operational viewpoint, will require a significant amount of interface and software development. No commercially available products integrate and control ALE-TADIL A operations for both fixed and airborne platforms.

It is possible that a system controller with the appropriate software could be integrated into one of the TADIL A control processors, or into one of the radio control units already acquired as part of the Canadian upgrade. The feasibility of this would have to be investigated further.[1]

1 As an example of the first steps toward such an integrated controller, the Harris Corporation demonstrated an ALE-TADIL data communications system in tests carried out in 1989 in connection with the ROVING SANDS exercise at Ft. Bliss, TX. This demonstration, which mainly showed operation of the two system components as hardware, involved only TADIL A reception. (The Harris RT-1446/URC PACER BOUNCE transceiver used for ALE alone in the demonstration is not capable of the independent sideband (ISB) operation.) No system controller or system controller software was demonstrated. The PACER BOUNCE transceiver (for which compatible 500- and 1000-watt power amplifiers are available) could be modified for ISB operation at reasonable cost as a relatively inexpensive alternative to the currently considered suite of Harris ground station equipment if further ground stations were contemplated. If use of a PACER BOUNCE was contemplated, an interface to allow split-site operation of transmitting and receiving antennas would also have to be developed. We should note that the PACER BOUNCE radio is not suitable for airborne applications.

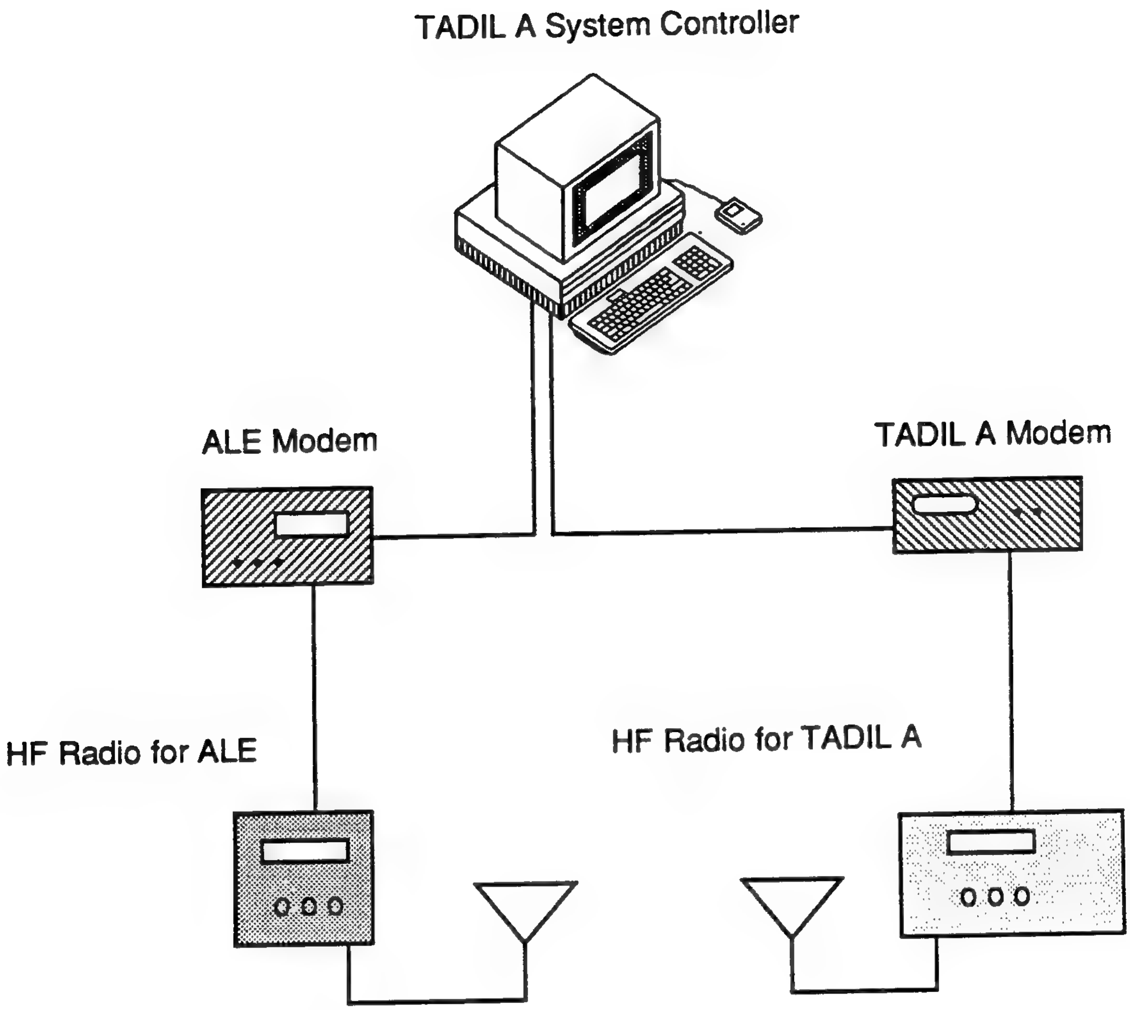

Figure B-1. Schematic Layout of a TADIL A Station with a System Controller

APPENDIX C

MORE ROBUST WAVEFORMS AND SIGNAL PROCESSING

Our tasking did not call for investigating the performance of the Tactical Digital Information Link (TADIL) A system itself after channels had been found by automatic link establishment (ALE). However, the relatively non-robust nature of the TADIL A waveform and error-correction scheme suggests that the ALE modem may link on channels that the TADIL modem cannot use effectively. If tests show that this happens frequently, then the use of more robust waveforms and signal processing might lead to better performance than with TADIL. Examples of such waveforms are the serial-tone, phase-shift keying (PSK)-modulated waveform prescribed by MIL-STD-188-110A (which is implemented in non-development item (NDI) modems), and a wideband (1-MHz bandwidth) waveform developed by MITRE for military applications and not yet in production.

In the absence of on-the-air tests, a descriptive comparison of the TADIL A and ALE waveforms and error-control schemes can provide some basis for predicting how well TADIL plus ALE might work in northern conditions, and whether or not more robust systems should be considered in current planning.

The TADIL system [10] uses a parallel-tone waveform in which 15 tones are modulated by quadrature phase-shift keying. Error control is provided by 5/6-rate Hamming coding. Some protection against fading and multipath is provided by long symbol durations and frequency diversity offered by optional independent sideband (ISB) operation. The Hamming coding can correct only one bit per 30-bit codeword, however, so it is not particularly robust.

The ALE system [1, 2] uses 8-frequency-shift keying (FSK)-modulated, serial-tone waveform with 1/2-rate Golay coding that can correct up to three errors per 24-bit codeword. The system also uses three-fold bit diversity and a (relatively short) interleaver. This combination of powerful error-control techniques provides a relatively large margin against the reception of erroneous data during link setup or link quality assessment (LQA) operations.

Therefore, it is not unlikely that the rapid fading and large multipath delay spreads encountered sometimes in the north will lead to situations in which ALE will work but TADIL A data exchange won't. To some extent, the ability of ALE to find new channels on short notice will restore throughput in these conditions, but there probably will be times (when signal paths are near the auroral oval or cross the night-day terminator) that the TADIL A modem simply cannot cope with the poor propagation conditions and data transmission fails.

At such times it is possible that a modem designed to deal with large multipath spreads and selective fading will be able to cope. The MIL-STD-188-110A modem mentioned above has powerful convolutional coding, a data-directed channel equalizer, and a long (ten seconds) interleaver that usually lead to much better performance in difficult channels than a

TADIL-type modem [11, 12]. Although it sometimes has difficulty maintaining synchronization in difficult channels, this modem may work better than the TADIL A modem, on average, in such channels.

Another modem that will generally work better than the TADIL A modem in disturbed channels is the wideband modem developed by MITRE. This modem uses a Rake equalizer that coherently combines most of the energy contained in signals spread by multipath. When equipped with suitable error-correction coding and a narrowband interference excisor, such a system has been shown to provide very effective communications in disturbed channels [6]. At least two vendors have demonstrated prototype wideband systems that might be suitable for TADIL data transmission in disturbed channels. Some versions of these systems have their own (nonstandard) automatic linking schemes. Such a system might be considered as an emergency backup to an ALE-TADIL system during northern operations.

In addition to the general phenomena of multipath and selective fading, northern channels sometimes show very rapid fading (high values of Doppler spread), especially at night. Reference [13] gives a synopsis of data on links from Barrow, AK, to Boulder, CO, and Thule, Greenland, to Palo Alto, CA, that sometimes exhibit Doppler spreads up to 20 Hz. These values are roughly ten times greater than those usually measured at midlatitudes. Whether or not a more robust waveform such as those referred to above can cope with such large Doppler spreads should be analyzed before a commitment to a particular robust modem is made. We recommend that on-the-air tests of such modems be carried out in conditions of rapid fading.

If it is determined that a more robust modem and an overall system controller are required in the RADIL system, the robust modem would take the place of the "TADIL A Modem" in figure B-1.

APPENDIX D

COST ESTIMATES

This appendix gives rough estimates of the cost of three upgrade options that may be considered as possibly cost-effective enhancements to the current two-fixed-station RADIL concept. These are:

- A version of the Harris RF-350 (RT-1446/URC PACER BOUNCE) transceiver modified for independent sideband (ISB) operation
- A system controller that would allow fully automatic automatic link establishment-Tactical Digital Information Link (ALE-TADIL) operation
- A more robust modem for TADIL A data transmission at high latitudes.

D.1 PACER BOUNCE UPGRADE

The RT-1446/URC PACER BOUNCE transceiver is an off-the-shelf high frequency (HF) radio that is capable of operating automatically with the Harris RF-7210 ALE controller. This transceiver can also operate automatically with the Harris RF-3230 1-kW, solid-state power amplifier to produce output consistent with the already procured equipment suite.

Figure D-1 shows a possible fixed-node configuration of a TADIL A node that uses a modified PACER BOUNCE transceiver. The figure also shows other equipment (a pre-/post-selector, antenna coupler, etc.) that might be required to assemble a fully functional TADIL A ground station.

The PACER BOUNCE transceiver does not transmit in the independent sideband (ISB) mode, and would have to be modified to do so. Furthermore, it was not designed for split-site (separated transmitting and receiving antennas) operation. A PACER BOUNCE system using a single transceiver would also require modification to amplify (or retransmit) received signals from the receiving site to the transmitting site. Alternatively, two modified PACER BOUNCE transceivers could be used, one at the transmitting site and one at the receiving site. Despite the need for at least one modification, it is possible that a modified PACER BOUNCE transceiver and power amplifier combination would be cheaper than the current equipment suite at RADIL sites.

Estimates made in 1992 of the cost of a modified PACER BOUNCE transceiver plus all the equipment shown in figure D-1 suggest that the suite might cost about $100K per fixed node.

D.2 SYSTEM CONTROLLER

Appendix B describes a system controller that would allow fully automatic coordination and operation of an ALE-TADIL-A combination. Developing such a controller would require new software and either a system-control computer or a modification of the current TADIL controller. In terms of the amount of work needed to produce a full-scale development of this software in accordance with DOD-STD 2167A, the cost of such a controller is estimated to be about 255 staff months. A "rapid prototype" of the software for such a controller could be produced in about 85 staff months. Both of these estimates are preliminary and are subject to revision by a formal cost estimation process.

D. 3 MORE ROBUST DATA MODEM

The use of a more robust data modem, such as a MIL-STD-188-110A serial- or parallel-tone type (whose suitability for TADIL operations in northern communications channels would have to be analyzed further), would require a new interface between the TADIL A controller and the new modem, and new software to implement the TADIL A protocol with the new waveform. Although a more robust waveform and error-correction scheme would probably lead to significant improvement in communications performance during northern operations, replacement of the current TADIL A modems with more robust modems would require systems analysis to answer questions about interoperability with current TADIL A modems, possible improvements of the TADIL A network protocols, etc. Such a replacement should not be considered before this systems analysis is done.

Off-the-shelf versions of MIL-STD-188-110A modems (which can use both serial- and parallel-tone waveforms) cost between $7K and $10K each in small quantities. Estimating the cost of an interface and possible new software to implement the TADIL A protocol using a different waveform would require further analysis.

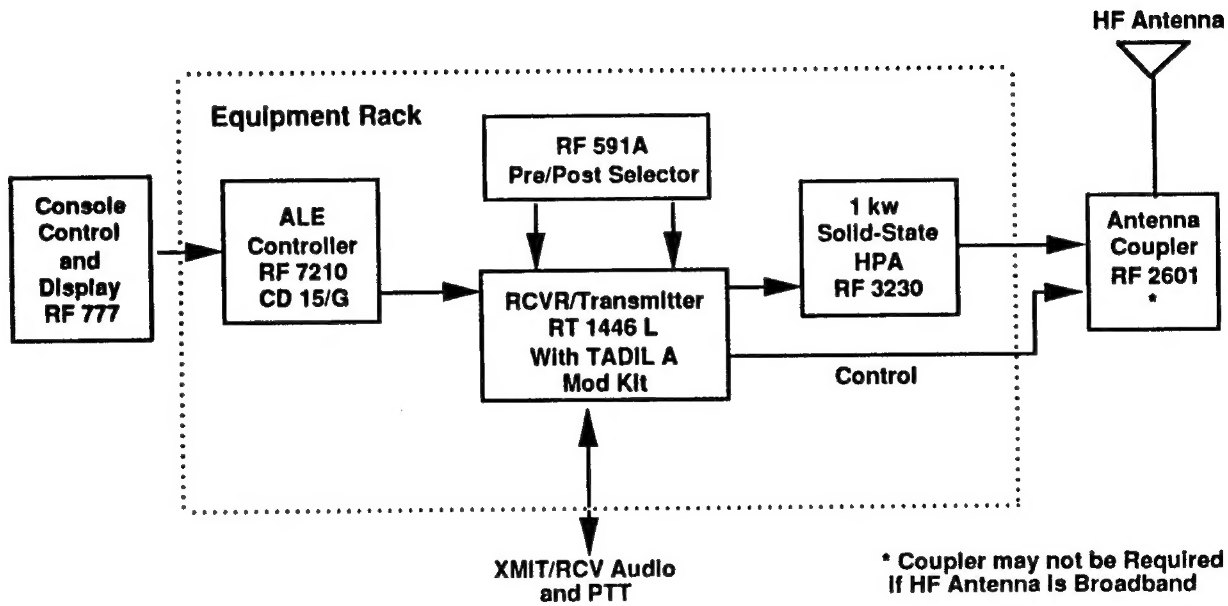

Figure D-1. Alternative Ground Station Configuration

APPENDIX E

LINK RELIABILITY WITH ALE AND CONVENTIONAL LINKING

Suppose that a Tactical Digital Information Link (TADIL) A node has N frequencies that it can use to set up a link or re-establish one if it starts to fail. With the current approach, the crew might reasonably try the frequency with the highest reliability among the N possible ones. For the benign links discussed above, this frequency would be around 85 percent of the maximum usable frequency (MUF). (The reliabilities of the N frequencies can be predicted by running the Ionospheric Communications Analysis and Prediction program (IONCAP) for the chosen link at the season, sunspot number, and times of interest.) The probability that this frequency actually leads to linking and subsequent TADIL A operation is by definition equal to the chosen frequency's reliability. Hence, at any time, the chance for successful linking with one attempt is

$$\max_i(r_i), \tag{1}$$

where r_i is the reliability of frequency i, and the symbol $\max_i()$ stands for the largest of the values in the parentheses for $i = 1, \ldots, N$. On the other hand, if the crew uses automatic link establishment (ALE), which will normally try all N frequencies on one attempt if necessary, then the probability of successful linking is just the probability that at least one of the N frequencies has a high enough signal-to-noise ratio (SNR) for linking. If the N channels are independent, then this probability is

$$1-\prod_{i=1}^{N}(1-r_i), \tag{2}$$

where the second term stands for the product of the N values of $(1 - r_i)$. This product is the probability that none of the N frequencies is reliable. (Eq. (2) is an upper bound on actual performance since the channels are not generally independent.)

To gain some insight into the meaning of Eq. (2), note that if the reliability of the ith frequency is high, then the corresponding value of $1 - r_i$ will be low, so that the ith frequency will lower the product significantly, raising the chance that at least one frequency will be found by ALE to have sufficient SNR for linking. Conversely, if the ith frequency has low reliability, that frequency will not raise the chance of ALE success.

GLOSSARY

ACP	Automatic Communications Processor
AFB	Air Force Base
ALE	automatic link establishment
AWACS	Airborne Warning and Control System
BER	bit error rate
CRC	Communications Research Centre (Ottawa, Canada)
FOT	optimal working frequency
FSK	frequency-shift keying
GMT	Greenwich mean time
HF	high frequency
IONCAP	Ionospheric Communications Analysis and Prediction Program
ISB	independent sideband
LBC	listen-before-call
LBDT	listen-before-data-transmission
LQA	link quality assessment
LUF	lowest usable frequency
MHz	megahertz
MTBF	mean time between failures
MUF	maximum usable frequency
NCS	net(work) control station
NDI	nondevelopmental item
NWT	Northwest Territories
PC	personal computer
PSK	phase-shift keying
RADIC	Rapidly Deployable Integrated Command and Control System
RADIL	Regional Operations Control Center AWACS Digital Information Link
RAM	random access memory
ROCC	Regional Operations Control Center

SNR signal-to-noise ratio
SSB single-sideband

TADIL Tactical Digital Information Link